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(NASA-TM-107839) AUTONOMOUS RENDEZVOUS AND
DOCKING CONFERENCE, VOLUME 3 (NASA) 301 p
N92-26045
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AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

Lyndon B. Johnson Space Center
Houston, Texas

August 15-16, 1990

Sponsored by

NASA Office of Space Flight

NASA Office of Aeronautics,
Exploration and Technology

NASA Space Servicing Systems
Project Office

Volume III

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

August 15-16, 1990

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

PREFACE

This document consists of the presentations submitted at the Autonomous Rendezvous and Docking (ARD) Conference. The document contains three volumes:

VOLUME I	ARD Hardware Technology
VOLUME II	ARD Software Technology
VOLUME III	ARD Operations

Information contained herein should not be construed as being the official NASA position. Responsibility for content and technical accuracy lies with each respective author.

The ARD Conference was sponsored by NASA Office of Space Flight, NASA Office of Aeronautics, Exploration and Technology, and NASA Space Servicing Systems Project Office.

James S. Moore
James S. Moore
Manager of NASA Space Servicing Systems Project Office
NASA-JSC
Code IA 141

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INTRODUCTION

Autonomous Rendezvous and Docking (ARD) will be a requirement for future space programs. Clear examples include satellite servicing, repair, recovery, and reboost in the near term, and the longer range lunar and planetary exploration programs. Indeed, ARD will permit more aggressive unmanned space activities, while providing a valuable operational capability for manned missions. The purpose of this Conference is to identify the technologies required for an on-orbit demonstration of ARD, assess the maturity of those technologies, and provide the necessary insight for a quality assessment of programmatic management, technical, schedule, and cost risks.

James S. Moore
ARD Conference Chairman

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Session III ARD OPERATIONS

Don J. Pearson
NASA-Johnson Space Center
Technical Session Chairman

AUTONOMOUS RENDEZVOUS AND DOCKING

OPERATIONS

SESSION III

SUMMARY

Don J. Pearson
NASA - Johnson Space Center

ARD OPERATIONS

- MSRM:
  - STILL ALIVE, EVALUATING LOTS OF ALTERNATIVES
  - AR&D STRONGLY EMPHASIZED
- FOCUS ALSO ON PRE-RELATIVE NAVIGATION PHASE
  - WHAT IS INFRASTRUCTURE AROUND MOON, MARS?
  - WHAT IS THE LEVEL OF AUTOMATION IN THIS PHASE?
  - IMPACT TO REL-NAV REQUIREMENTS
    - ACQUISITION
    - ACCURACIES
- REVIEWED REL-NAV SENSOR REQUIREMENTS:INSIGHT VIA SHUTTLE SOR PROFILE, COELLIPTIC
- ROLE OF MAN IN AUTOMATED RENDEZVOUS
  - TELEOPERATIONS FLEXIBLE BUT AT COST: TDRS, LIGHTING, TIME LAGS

ARD OPERATIONS
(cont'd)

- REQUIREMENTS $\rightleftarrows$ DESIGN
  - INTERACTION
  - EVOLUTION, PROGRESSIVELY AUTOMATE (BY PHASE) AND IMPROVE
- DEVELOP A SIMPLE STRAIGHT-FORWARD SYSTEM FIRST
  - NEAR TERM
  - COOPERATIVE, "NICE" TARGET
  - SUPERVISED AR&D
  - SHUTTLE CAPABILITIES "ALMOST THERE"
    - PERHAPS LASER, SMALL FSW MODS, MECHANISM
  - CAN DO IT TODAY
- EVOLVE
  - AUTOMATE WHERE FEASIBLE, ADVANTAGEOUS
  - EVOLVE TO ABSORB PLANNING, TRAFFIC CONTROL, CONTINGENCY PLANNING

ARD OPERATIONS
(cont'd)

- MAINTAIN/EMPHASIZE
  - STRONG INTERACTION BETWEEN OPERATIONS + ENGINEERING
    - SENSORS
    - SOFTWARE
    - MECHANISMS
- PROX OPERATIONS = (5000' + 1000' + 3000' + 6000')/4 ~ 3700'

ARD OPERATIONS

ABSTRACTS

A Phased Approach to the Development of an Integrated Guidance, Navigation, and Control System for Autonomous Rendezvous and Docking:

CSDL Phased AR&D System Development: Introduction

Peter M. Kachmar
C. S. Draper Laboratory, Inc.
555 Technology Square
Cambridge, MA. 02139

A phased approach to the definition of the detailed IGN&C system requirements for an autonomous rendezvous and docking has been developed based upon our involvement in the Apollo, Skylab, ASTP, and Shuttle programs. This approach has included considerations in sensor requirements, integrated Guidance, Navigation, and Control system requirements, trajectory design, and mission operations.

Navigation system areas discussed include relative sensors and measured relative state parameters, sensor accuracy requirements, measurement intervals, and navigation filter design and operation.

Guidance/Targeting and maneuver execution areas discussed include use of IMU and appropriate threshold control for accelerometer bias, maneuver execution, and profile design.

Trajectory design deals with profile constraints, ease of sensor acquisition, dispersion handling capability and navigation tracking constraints. Control areas discussed include automatic translational maneuvering, actuator selection, and control system accuracy requirements.

Operational issues for each topic are addressed.

A Phased Approach to the Development of an Integrated Guidance, Navigation, and Control System for Autonomous Rendezvous and Docking:

Performance Analysis of a Candidate AR&D System Design

Peter M. Kachmar, Martin Matusky, Robert Polutchko,
Darryl Sargent, and Neil Adams
C. S. Draper Laboratory, Inc.
555 Technology Square
Cambridge, MA. 02139

This presentation addresses the integrated guidance, navigation and control system performance for the proposed autonomous rendezvous and docking (ARD) IGN&C system design, based on a phased enhancement of Shuttle-type system requirements. Results to date indicate performance of this candidate system will satisfy softdock requirements of 1.00 ft/s and 0.1 ft/s closing velocities.

The need for the development of guidance/targeting, navigation and control system requirements, in the context of integrated system performance will be discussed. ARD system performance with several target vehicle configurations are presented. Detailed IGN&C system performance data for several trajectory controllers, navigation sensor configurations, and system operations procedures are shown.

System performance figures of merit, including navigation accuracy, trajectory control corridors, fuel usage, and target impingement forces and torques are discussed. Use of the system in an augmented manual mode will also be discussed.

Improvements to the current IGN&C system performance is addressed, including the discussion of proposed control system modifications.

A Phased Approach to the Development of an Integrated Guidance, Navigation, and Control System for Autonomous Rendezvous and Docking:

Advanced Developments for Proximity Operations

Neil Adams
Edward Bergmann
Robert Polutchko
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Several advanced concepts for proximity operations are under development at our facility. Some of these concepts have shown significant performance benefits over current proximity operations schemes such as fuel efficiency, robustness to modelling uncertainty and disturbances, accommodations of evolving contingencies or constraints, and expanding the range of options to obtain mission goals. This presentation is a brief survey of three areas of development.

A highly augmented system for proximity operations, including features of offset point control, coordination of translation and rotation, and a high degree of fault accommodation, has been developed and demonstrated. This system has been extended to an automated system for on-board planning and fuel efficient execution of proximity operations subject to time and space constraints, including plume and collision avoidance. The heart of this system is an intelligent planner and execution system which comprises guidance and control integrated at the design stage rather than subsequent to point design development. The system is described, and several examples, including evasion of static and moving obstacles, limiting plume impingement on the target, and meeting constraints on closing rates are discussed.

A cooperative autopilot which simultaneously controls the relative motion (translation and rotation) of two spacecraft have been developed, coded, and tested. The autopilot consists of a two-burn targeting algorithm, a phase space position and attitude regulator, and a simple optimal jet selection algorithm. The cooperative autopilot has demonstrated fuel savings of as much as 37%, a decrease in the number of jet firings of 57%, and significantly greater accommodations of jet failures compared to traditional passive target/active pursuit vehicle techniques.

The final topic is a survey of recent advances in the area of robust control theory and their application of autonomous rendezvous and docking (ARD). These techniques produce special compensators that simultaneously design an estimator and compensator for the given open-loop system. The survey qualitatively examines the relative merits of each of these compensators for application to the ARD problem, and identifies the performance objectives for the various ARD phases of operation, i.e., rendezvous, proximity operations, and docking.

Spacecraft Rendezvous Performance Requirements Review

Don J. Pearson
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Perhaps the most difficult part of developing an automated rendezvous capability is defining a sensor suite to support relative navigation. Only after the chaser vehicle has sufficient knowledge of it's position and velocity with respect to the orbiting target vehicle can the chaser compute and execute maneuvers to rendezvous with the target. This presentation consists of an overview of the phases of rendezvous, starting with the timing of the launch from a planetary surface into the retrieval orbit, through proximity operations and docking. The discussion focuses on a detailed description of relative navigation performance requirements which can be expected for typical rendezvous missions during the last one hundred kilometers.

Range, range rate, bearing, and bearing rate limits and accuracies are presented with acquisition search volumes and search times.

Operational Requirements and Constraints in Autonomous and Remotely Controlled Rendezvous/Docking Missions

Hans F. Meissinger
TRW Space and Technology Group
Redondo Beach, CA

Remotely controlled rendezvous/docking sequences are subject to stringent constraints on target detection and tracking conditions and two-way orbit-to-ground communication characteristics in the feedback control loop. Relay link delays and operator perception lag affect remote control performance.

Fully autonomous control avoids these constraints and ideally would provide uninterrupted rendezvous/docking opportunities, around the clock. In practice, remote monitoring and supervisory control of unmanned satellite rendezvous and docking sequences by a ground-based operator may still be desirable, at least as a transitional step before full autonomy is to be introduced, and thus imposes some of the above constraints.

This presentation outlines the sensing, viewing and communication and control requirements that apply at various levels of rendezvous/ docking autonomy, and presents results of comprehensive analyses of the underlying orbital geometry, orbital mechanics, proximity operations and control system characteristics. Of particular interest are the implications on mission timelines, propulsion requirements and permissible daily rendezvous/docking windows. Operational safety and collision avoidance provisions suitable for use in the event of a control system malfunction will also be discussed.

Operational and System Dependent Considerations and Constraints for Designing an Autonomous Rendezvous or Docking System

Christian K. Meyer
Rockwell International
600 Gemini
Houston, TX 77058

A robust autonomous rendezvous and docking (ARD) system should be flexible enough to cope with changing mission objectives and vehicle capabilities. Depending on the degree of complexity and maturity desired, the system must address both nominal and off-nominal situations. Simply getting from point A to point B is only a part of the solution to any rendezvous task. Nominal considerations include mission objectives, target contamination concerns, stopping points (delay capability), obstacle avoidance, and navigation state updates. Off-nominal operations include system redundancy, system reconfiguration, and breakouts (trajectory aborts).

The presentation discusses topics both directly and indirectly related to the design of an ARD system. Emphasis is placed on the ARD system interrelationship with vehicle constraints and interfaces outside the typical autonomous system, rather than the specifics of control and targeting.

Vehicle constraints deal with jet redundancy (translational and rotational control), sensor redundancy (fallback options, impact on knowledge of state when sensor has failed), contamination concerns (a function of the target's sensitivity to the chaser's jet plume flowfield). Additional interfaces include uplink of state vectors, comparison of sensor vector vs. ground vector, target requests for rendezvous delay, three-body problems, obstacle avoidance considerations, and the possibility of an active target.

System Architecture for Autonomous Rendezvous and Docking

D. P. Dannemiller
Rockwell International
600 Gemini
Houston, TX 77058

A high level system architecture is developed. Development starts by dividing the mission into phases. During each phase, emphasis shifts to different aspects of the problem. The differences/pros/cons between automated and autonomous are discussed. Several mission classes/scenarios are described and a suggested system architecture is presented. The architecture is discussed with respect to the above considerations, i.e., mission phases, automated vs. autonomous, and mission classes.

Automation Issues for Rendezvous and Proximity Operations

Robert N. Lea
NASA - Johnson Space Center
Houston, TX 77058
and
Yashvant Jani
LinCom Corporation
Houston, TX 77058

There are several areas in rendezvous and proximity operations that will benefit significantly from the application of automation and autonomous concepts. The objectives in this presentation are to: (1) discuss those operational areas where autonomous operations are feasible, advantageous and enhance mission success, (2) identify the issues and concerns that require resolution prior to an autonomous space operations mission, and (3) describe our current activities that directly support autonomous operations. A typical satellite servicing mission scenario is described with major segments of the trajectory identified in terms of relative distances. An autonomous robotic spacecraft can easily approach a manned base in a similar fashion and perform docking operations under crew supervision. Major functions performed by this robotic spacecraft during this approach are: trajectory planning, guidance and navigation during all segments, and control of its own trajectory. A major function performed by a manned base during this type of mission is the mission monitoring. Intelligent sensors, working at the command level, can significantly enhance this monitoring function.

There are several issues in each of these functional areas that need to be resolved before an autonomous rendezvous and docking mission is undertaken. Some of these are: standardization of trajectory profiles, size and shape of the approach corridor, control zones, control authority and a level of cooperativeness, development of Design Reference Missions, sensor capabilities, methods to override autonomous control, crew training, trajectory control, and communication between the two spacecraft.

Our current efforts include development of applications based on fuzzy logic, Dempster-Shafer theory of handling uncertainty, and neural networks. For proximity operations, a controller is developed based on fuzzy sets for translational control of an active vehicle in approach, station keeping and fly around of a target vehicle. An attitude control capability based on a fuzzy phase plane approach has been developed for an active vehicle. Preliminary results of applications of the trajectory controller are presented. We are currently studying automated methods of mission planning that can deal with contingencies as well as nominal plans. For the rendezvous segment, we are studying the use of new technologies for adaptive control and adaptive filtering for more robust GN&C systems. Within the intelligent sensor area, a concept for a camera tracking system based on fuzzy logic has been developed. New technologies for object identification and caution/warning capabilities are currently being studied.

AR&D Strategies for a Mars Sample Return Mission

Stephen Bailey
NASA - Johnson Space Center
Houston, TX 77058

The presentation will briefly discuss the autonomous rendezvous and docking strategies studied for the Phase A Mars Rover Sample Return (MRSR) mission. The MRSR mission study was lead by the Jet Propulsion Laboratory, with the Johnson Space Center (and their contractors Martin Marietta Corp., and TRW) responsible for design of the delivery and return spacecraft. Because of President Bush's Space Exploration Initiative (SEI), MRSR study work has been vectored to look at alternate concepts for the sample return which may be more responsive to SEI objectives. The implications of these alternate concept studies on autonomous rendezvous and docking requirements will be explored, and audience questions and participation will be encouraged.

Autonomous Proximity and Docking Technologies

Robert L. Anderson
Roy K. Tsugawa
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Redondo Beach, CA 90247
and
Thomas C. Bryan
NASA - Marshall Space Flight Center

Autonomous spacecraft docking operations are being performed using a full scale motion-based simulator and an optical sensor. This presentation will discuss the work in progress at TRW to study the problem of autonomous proximity and docking operations. The docking sensor used is the MSFC Optical Sensor and simulation runs are performed using the MSFC Flat Floor Facility. The control algorithms and 6 DOF simulation software were developed at TRW and integrated into the MSFC facility.

Key issues being studied are the qualification of docking sensor requirements and operational constraints necessary to perform autonomous docking maneuvers, control algorithms capable of performing autonomous docking in the presence of sensitive and noisy sensor data, and sensor technologies for autonomous proximity and docking operations. As a part of this study, the MSFC sensor characteristics were analyzed and modeled so that off line simulation runs can be performed for control algorithm testing. Our goal is to develop and demonstrate full 6 DOF docking capabilities with actual sensors on the MSFC simulator.

Results from actual docking simulation runs, which show sensor and control loop performance as well as problem areas, will be presented. The evolution of various control algorithms using both phase plane and Clohessy-Wiltshire techniques are discussed. In addition, 6 DOF target acquisition and control strategies are described.

ARD OPERATIONS

PRESENTATIONS

A PHASED APPROACH TO THE DEVELOPMENT OF AN INTEGRATED GUIDANCE, NAVIGATION, AND CONTROL SYSTEM FOR AUTONOMOUS RENDEZVOUS AND DOCKING

CSDL PHASED AR&D SYSTEM DEVELOPMENT: INTRODUCTION

AUTONOMOUS RENDEZVOUS AND
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August 15-16, 1990
P. KACHMAR

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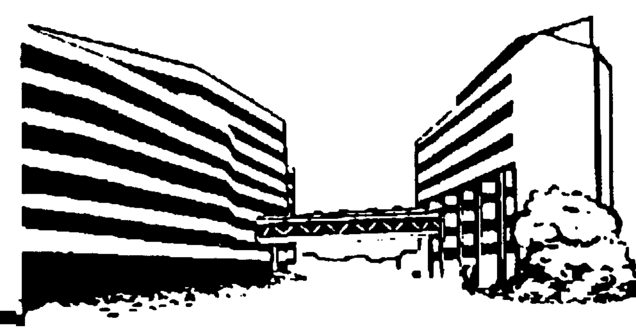


CSDL PRESENTATION OVERVIEW

— The three AR&D conference papers illustrate the <u>phased</u> approach to the development of an AR&D system being pursued at CSDL

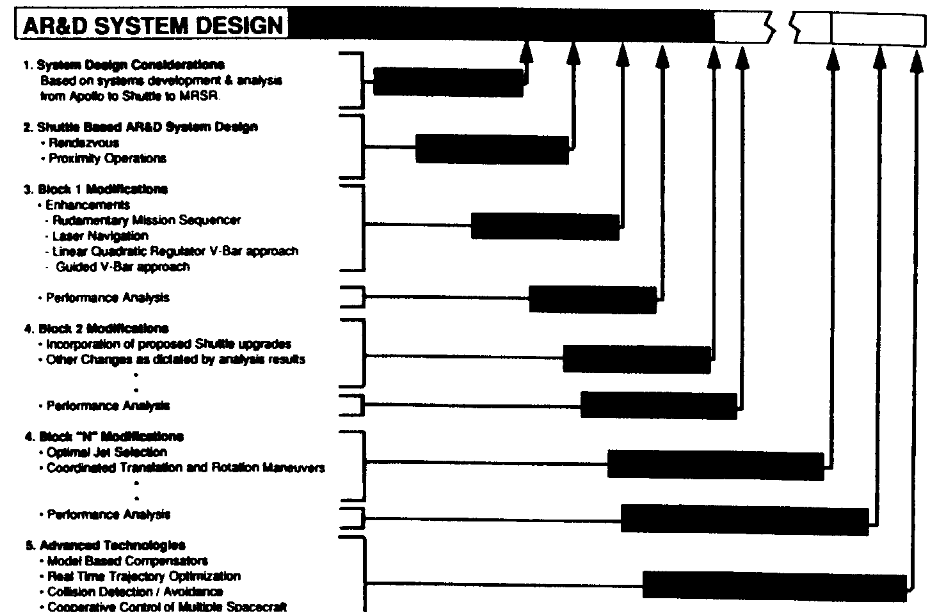
— These presentations will discuss the following:

- IGN&C System Design considerations and Candidate design
- Candidate Design Performance Results
- Advanced Development for Proximity Operations

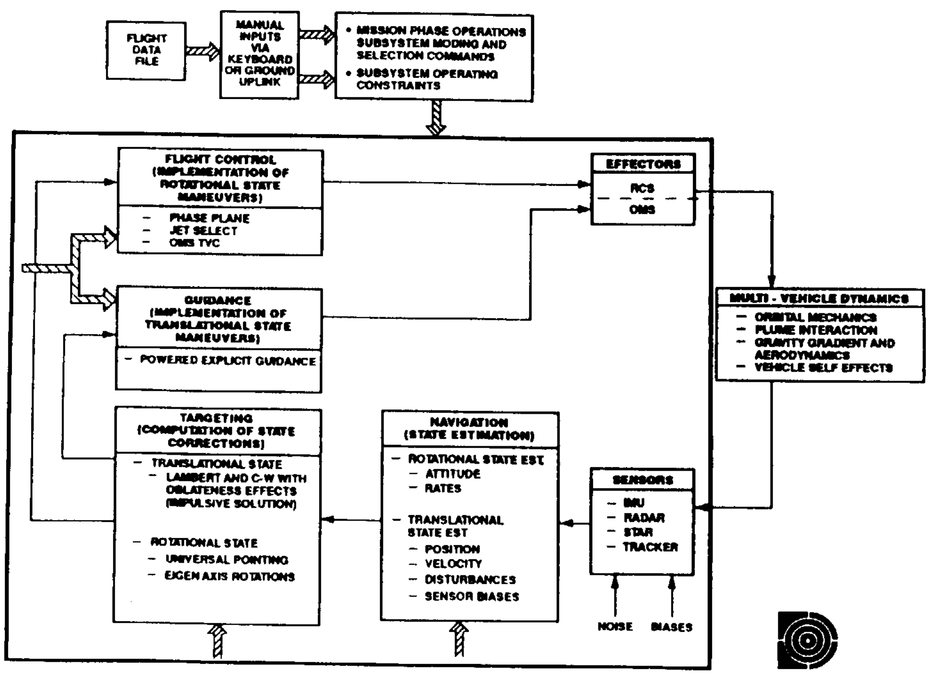
— It is planned to separately document the extensive supporting performance data in a set of CSDL memos which will be distributed to interested parties

— The following chart illustrates the phased development approach

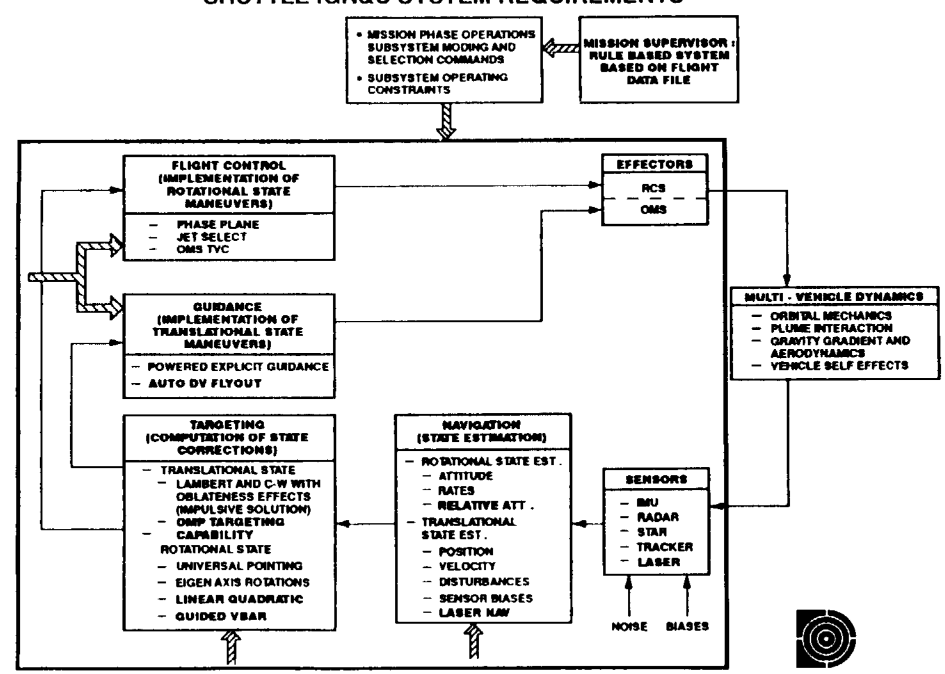
Phased AR&D System Development



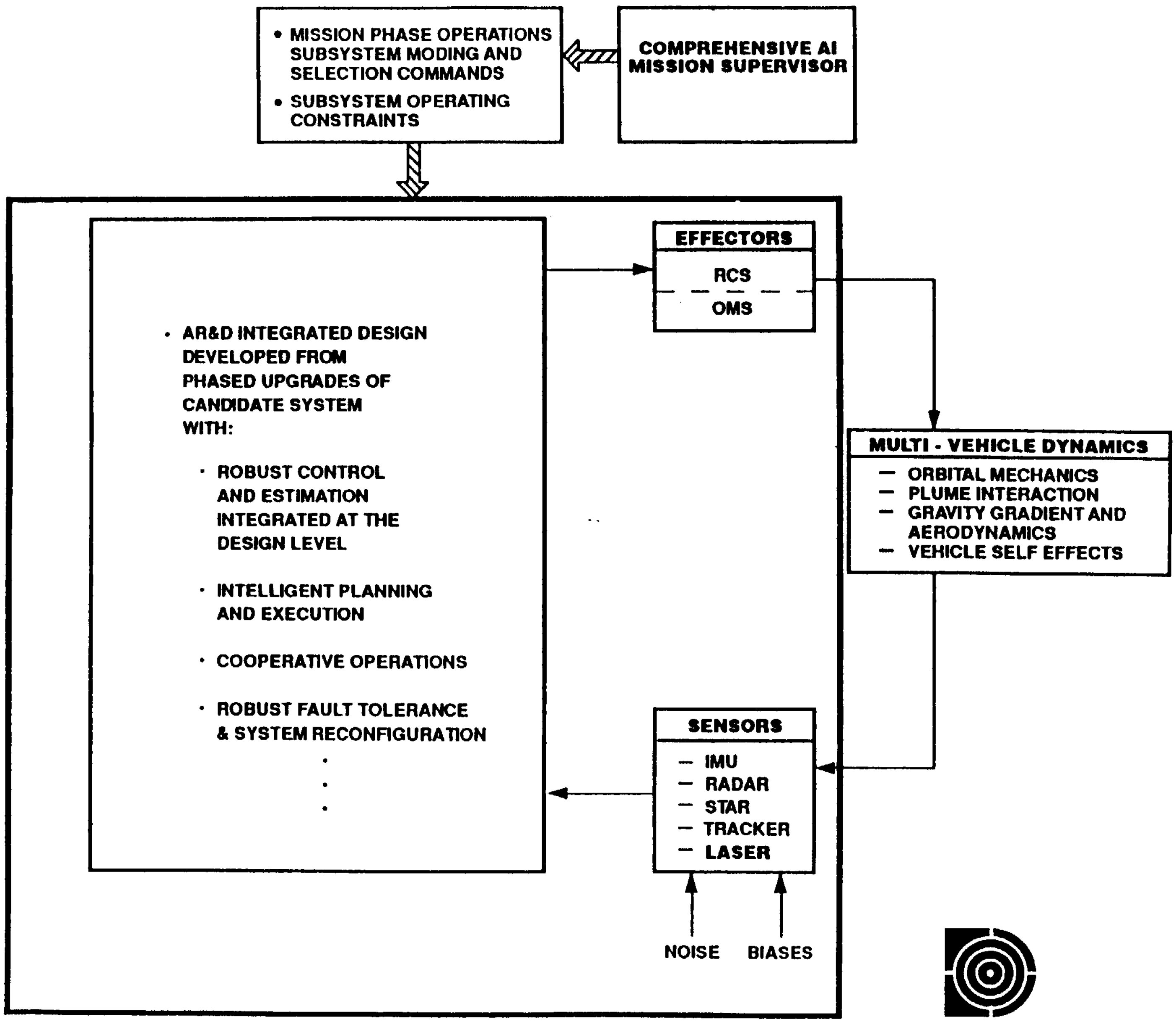
SHUTTLE IGN&C SYSTEM SCHEMATIC



AR&D CANDIDATE SYSTEM DEVELOPED FROM SHUTTLE IGN&C SYSTEM REQUIREMENTS



ADVANCED AR&D SYSTEMS DESIGNS



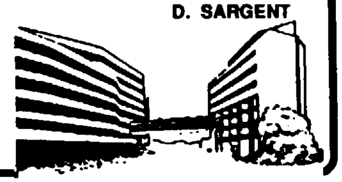
A PHASED APPROACH TO THE DEVELOPMENT OF AN INTEGRATED GUIDANCE, NAVIGATION AND CONTROL SYSTEM FOR AUTONOMOUS RENDEZVOUS AND DOCKING

DESIGN CONSIDERATIONS AND CANDIDATE DESIGN

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE
August 15-16,1990

P. KACHMAR
D. SARGENT

THE CHARLES STARK DRAPER LABORATORY, INC.



OUTLINE

- AR&D IGN&C System Development
  - — Top level requirements
  - — Rendezvous and Prox OPS phase discussion
  - — System AREAS to be discussed
- Design considerations
  - — Rendezvous mission phase
    - IGN&C System
    - Navigation
    - Guidance/Targeting
    - Control
  - — Proximity Operations mission phase
    - IGN&C System
    - Navigation
    - Guidance/Targeting
    - Control
- Candidate design

AR&D IGN&C SYSTEM DEVELOPMENT

CSDL

AR&D IGN&C SYSTEM TOP LEVEL REQUIREMENTS

- Rendezvous mission phase
  - Bring the active vehicle to the start of the proximity operations phase within a specified 3σ dispersion ellipse relative to the target
  - Satisfy trajectory and consumable constraints
  - Accomplish the above with:
    - dispersed conditions at the start of rendezvous
    - sensor failures and subsequent system reconfiguration
- Proximity operation mission phase
  - Maintain the relative position, velocity and attitude between the chaser and target vehicle along a desired relative approach profile
  - Control docking conditions consistent with docking mechanism capabilities
  - Accomplish the above with:
    - dispersed initial conditions
    - sensor failures and subsequent system reconfiguration

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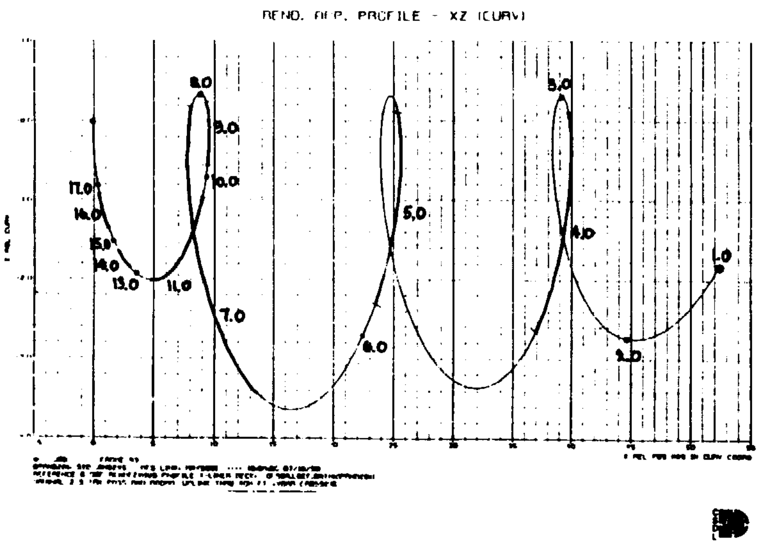
RENDEZVOUS AND PROXIMITY OPERATIONS PHASE DISCUSSION

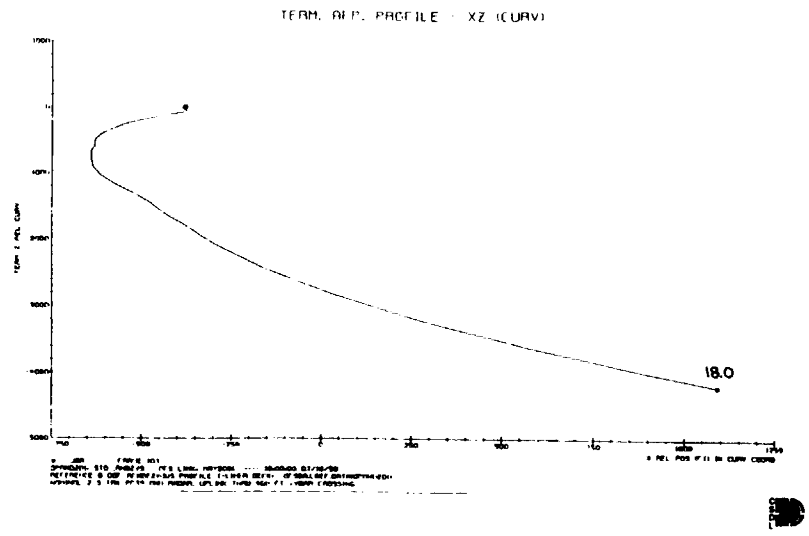
- Definitions
  - Rendezvous phase
    - Consists of IGN&C system operation (relative nav, targeting and guidance of rendezvous maneuvers, and control of the vehicle during maneuver execution and sensor tracking), to bring the active vehicle to the prox ops mission phase
      - Relative ranges can be on the order of several hundred miles
  - Proximity operations phase
    - Consists of IGN&C system operation required to bring the active vehicle from the final rendezvous midcourse correction (or start of prox ops phase) to docking. It includes:
      - Braking
      - Line of sight control } if required
      - Station keeping } if required
      - Approach to docking/berthing conditions
    - Considered to be operations within 1 nm of the target vehicle

CSDL

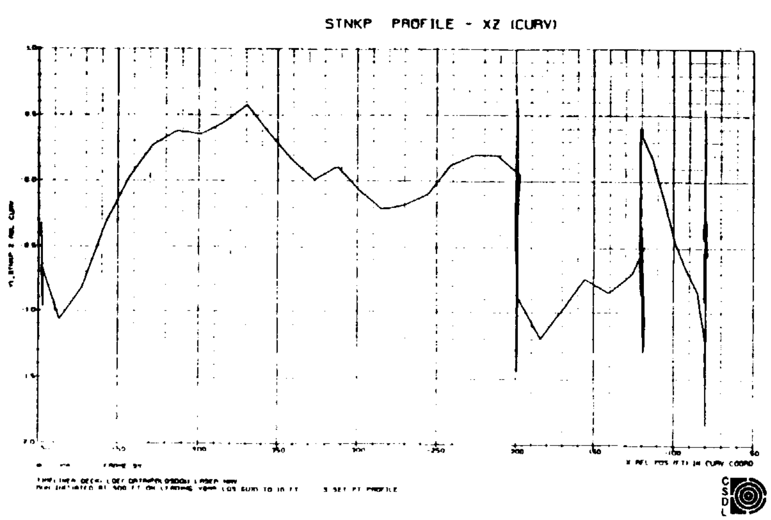
LDEF RENDEZVOUS PROFILE



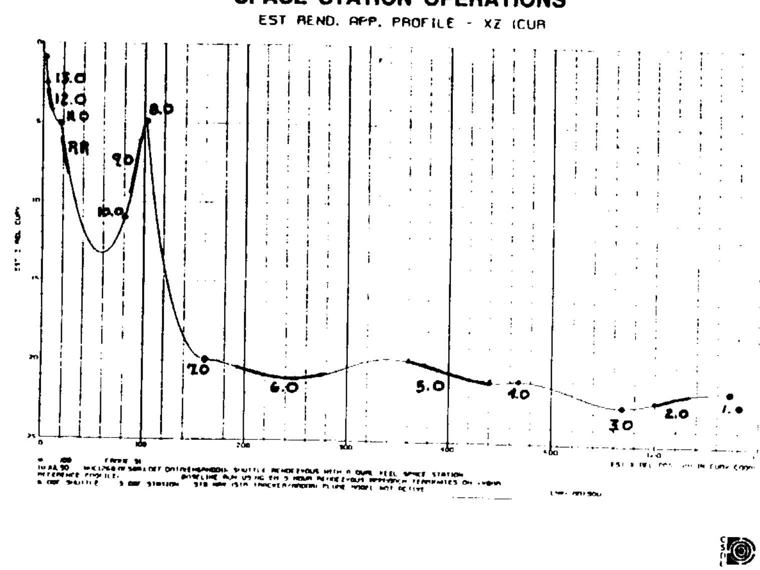
LDEF TERMINAL PHASE PROFILE
MCC4 TO VBAR STATIONKEEPING



LINEAR QUADRATIC REGULATOR: VBAR APPROACH
CASE L1:
- Baseline AR&D System
- No plume on target



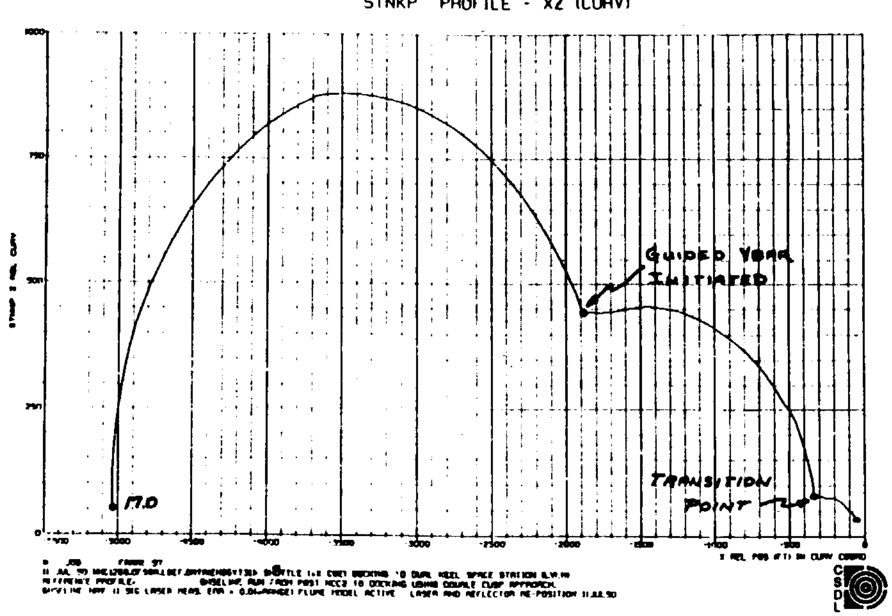
A LONG RANGE RENDEZVOUS PROFILE FOR SPACE STATION OPERATIONS



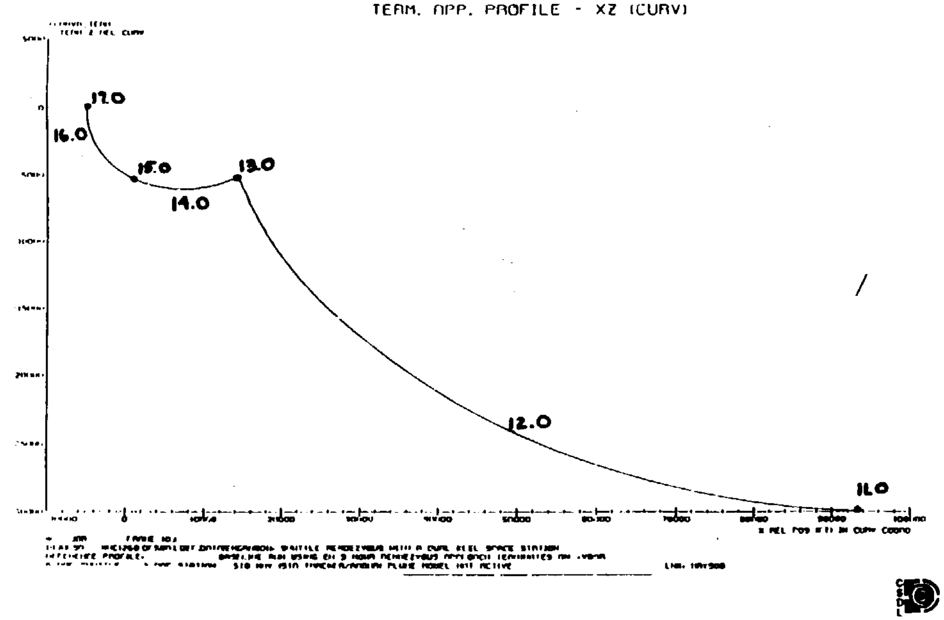
GUIDED VBAR APPROACH

CASE G1: - Baseline AR&D System

- With plume effect on heavy target



A LONG RANGE RENDEZVOUS PROFILE FOR SPACE STATION OPERATIONS (cont'd)



RENDEZVOUS AND PROXIMITY OPERATIONS SYSTEM AREAS TO BE DISCUSSED

- IGN&C System
  - — System level requirements
- Navigation
  - — Discussion of sensors and the relative state parameters measured
  - — Sensor accuracies
  - — Requirements on measurement intervals
  - — Filter design/operation
- Guidance/Targeting, Maneuver Execution, and Profile Design
  - — Profile design
    - Constraints
    - Ease of sensor acquisition
    - Dispersion handing capability
    - Relative navigation track intervals
  - — IMU considerations (used to sense velocity change)
    - Threshold control for accelerometer bias
  - — Translational maneuver execution
    - Orbital Maneuvering System Guidance
    - RCS auto maneuver ΔV flyout
- Control
  - — Thruster Requirements
    - Placements
    - Type
    - Size
  - — Control Algorithm
  - — RCS Moding

CSDL

SYSTEM DEVELOPMENT

- The set of rendezvous and prox ops IGN&C system design considerations in this paper have been developed from CSDL involvement in Apollo, Skylab, and Shuttle programs in the following areas:
  - — GN&C point design development
  - — Integrated GN&C system requirements development
  - — Trajectory design
  - — Mission operations development
  - — Integrated GN&C performance analysis
- The candidate AR&D system developed from this set of design considerations:
  - — Represents a starting point for evolutionary design development
  - — Is based on a phased enhancement of shuttle type IGN&C system requirements
  - — Is supported by extensive performance analysis
  - — Is a generic design, not tailored to a specific vehicle
  - — Provides a baseline for an initial AR&D system with modifications easily made as required for improving performance

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PERFORMANCE ANALYSIS APPROACH

- Simulation techniques
  - — Linear covariance analysis techniques, IGN&C high fidelity 6 DOF deterministic simulations, as well as guidance, navigation and control engineering simulations, have been used to obtain system performance data to support the design considerations presented here
  - — Rendezvous phase analysis used the following
    - Linear covariance simulations: while recognized as having shortcomings in certain applications (where non-linear effects dominate), it has proven reliable in rendezvous phase guidance, targeting and navigation analysis by comparison with independent IGN&C Monte Carlo analysis results
    - High fidelity IGN&C deterministic simulations: used to ascertain the effects of finite vehicle size (e.g., C.G. to IMU offset) and control system rotational/translational interaction effects on system performance.
      - Navigation results from these simulations are used to refine the linear covariance analysis simulations, increasing the fidelity of the linear covariance results
    - Guidance, Navigation and Control Engineering Simulations:
      - Used to develop/analyze initial G,N and C point designs

PERFORMANCE ANALYSIS APPROACH (cont'd)

- Prox ops phase analysis used the following
  - — High Fidelity IGN&C 6 DOF deterministic simulations: required for analysis since errors and dispersions are comparable in size to the relative range, and GN&C interaction effects have a major impact on integrated system performance
- The system performance data to support the material in the presentation has been obtained from simulations using Shuttle flight software requirements as a baseline and the appropriate system modifications required to meet an initial set of AR&D system performance specifications.
- The need for the development of an AR&D system in an integrated GN&C systems context will be demonstrated

RENDEZVOUS MISSION PHASE DESIGN CONSIDERATIONS

CSDL

IGN&C SYSTEM CONSIDERATIONS

- System is required to place chaser vehicle at the proximity operations initiation point within a well defined 3σ dispersion ellipse with:
  - — System failures
  - — Dispersed conditions at the start of rendezvous
- Maximize onboard system capability for use at long ranges from the target
- Satisfy consumable requirements
- Appropriate level of fault tolerance
- Ability to reconfigure IGN&C system in response to system failure
- Relatively "coarse" requirements are placed on the accuracy of translational maneuver execution and on rotational (attitude) control

NAVIGATION

- Ultimate goal is to estimate the relative state (position, velocity) between two vehicles
  - — This can be achieved by measuring the relative state directly or by using high quality estimated inertial states to derive the relative state
  - — Part or all of the six components of the relative state (range, range rate, angles, angle rates) can be measured
  - — By use of appropriate filtering techniques, only a portion of the relative state needs to be measured, the remainder being derived from the correlations in the filter
- Typical rendezvous sensors which measure part or all of the relative state directly:
  - — Rendezvous radar: range, range rate, angles, angle rates
  - — Optical sensors: angles only
    - Star tracker
    - COAS (manual operation)
  - — Ranging device (e.g., VHF range on CSM)
  - — LASER: range, rate-rate, angles, angle rates

NAVIGATION (cont'd)

- Relative nav sensors
  - At long ranges
    - High quality angle measurements are desired since relative position error normal to the active-passive vehicle line of sight is proportional to range times the angle error
      - Thus the Shuttle star tracker is preferred over the rendezvous radar at long ranges since radar angle quality is worse
      - Long range rendezvous maneuvers are targeted very accurately using angle only measurements even though estimates of range and range rate are poor
      - Acquisition of target may be easier with radar since star tracker requires either sunlit target or cooperative light on target and may lock on to a "false" target (stars)
      - For radar acquisition > 26 nm, Shuttle quality radar requires a transponder on the target
      - Radar angle rates are not essential to satisfactory relative state estimation
      - Range and/or range rate combined with star tracker quality measurements are desirable, but not necessary

NAVIGATION (cont'd)

- Relative nav sensors (cont'd)
  - Short range
    - Rendezvous radar is preferred since it can track target under all conditions
      - No sunlight constraints
      - Less chance of acquiring false targets
    - Angle measurement quality not as critical as in long range tracking
    - Full relative state measurements are not essential but are preferred since they would provide better relative state knowledge for handover to proximity operations mission phase
      - Angles only would support satisfactory targeting of midcourse corrections and would permit prox ops sensor acquisition

      (Less accurate COAS is also acceptable at short ranges but requires manual operation)

NAVIGATION (cont'd)

- Discussion of relative parameters measured
  - In planning for future missions or considering failed sensor operation the following describes performance to be expected for each measurement type:
    - Angles only
      - Satisfactory to complete rendezvous
      - Provides resolution of nav errors normal to line of sight
        - Resolves crosstrack and in plane normal state errors
      - Provides accurate targeting solution to accomplish rendezvous despite unresolved errors along LOS

NAVIGATION (cont'd)

- Discussion of relative parameters (cont'd)
  - Range or range and range rate
    - Solves in plane problem satisfactorily
    - Crosstrack errors unresolved even with filter. Thus unsatisfactory measurement set for a rendezvous which has sizable crosstrack errors
    - If crosstrack left unresolved until acquisition by short range sensor, crosstrack corrections may not be able to be combined (RSS'd) with in plane maneuver, resulting in a (possible large) fuel penalty

NAVIGATION (cont'd)

- Discussion of relative parameters measured (cont'd)
  - Range, range rate and angle combination
    - Addition of range rate to range and angle measurement combination does not improve steady state system performance
    - If range measurement is lost, range rate provides slight improvement over radar angles alone
    - Reasons for adding range to the angle measurements
      - If angle measurement quality is poor (for example radar angles or large platform misalignment) range significantly aids sensor angle bias estimation and platform in plane misalignment estimation, resulting in improved maneuver targeting
      - If angle quality is good, range provides small total state errors for prox ops sensor initialization

NAVIGATION (cont'd)

- IMU considerations
  - Used to sense maneuvers
    - If maneuvers sensed poorly, relative state sensor quality must be such as to solve the resultant velocity error. Length of time to resolve error is dependent on sensor quality
    - If not at C.G., have to correct for effects of rotation being sensed as translation
    - Effect of accelerometer bias can be ameliorated by appropriate selection of sensed velocity threshold
  - Provides body attitude for relating angle measurements to inertial frame
    - Quality of IMU alignments and drift affects quality of angle measurements
  - Want to avoid RM IMU switching if the system is so configured to avoid degrading nav performance due to changing nav measurement residuals

NAVIGATION (cont'd)

- Alternate relative state determination
  - GPS
    - Use of high quality inertial state estimation for both active and passive vehicles provides a relative state accurate enough for rendezvous mission operations
    - Requires communication link between the two
  - Ground/DSN
    - Quality of ground navigation of active and passive vehicles determines the smallest relative ranges at which rendezvous maneuvers can be supported
    - Requires long ground track arcs and hence long times between maneuvers to resolve maneuver execution errors
    - Need to consider communication times for updates
    - Therefore, not adequate for short relative ranges or critical maneuver support

SENSOR ACCURACIES

- The following sensor accuracies are for the Shuttle system specifications and are adequate to effect a successful autonomous rendezvous mission

STAR TRACKER MISALIGNMENT AND STAR SIGHTING ERRORS

- Star tracker alignment uncertainty (1σ)
  - Star tracker to navigation base misalignment
    - w_X 22.8 arcsec
    - w_Y 22.8 arcsec
    - w_Z 20.6 arcsec

- Star sighting errors (2-axis, 1σ)
  - Random star (target) position errors 15.0 arcsec
  - Star (target) sighting biases 16.0 arcsec

RADAR PARAMETER MEASUREMENT LIMITS

PARAMETER	PASSIVE MODE	ACTIVE MODE
LOS range	100 ft (30 m) to 100 nmi (190 km)	100 ft (30 m) to 300 nmi (560 km)
LOS range rate	148 ft/s (45 m/s) closing, 75 ft/s (23 m/s) opening	1500 ft/s (457 m/s) closing, 300 ft/s (91 m/s) opening[a]
LOS pitch angle (relative to Orbiter -Z axis)[b]	±30 deg	±30 deg
LOS roll angle (relative to Orbiter -Z axis)[b]	same as pitch	same as pitch
Pitch inertial angle rate	±20 mr/s	±20 mr/s
Roll inertial angle rate	±same as pitch	same as pitch

a. The LOS range limits versus range shall be as follows:
1500 ft/s closing, 300 ft/s opening at 300 nmi
700 ft/s closing, 300 ft/s opening at 300 nmi
300 ft/s closing, 300 ft/s opening at 100 nmi
200 ft/s closing, 300 ft/s opening at 50 nmi
148 ft/s closing, 75 ft/s opening at 10 nmi to 100 ft

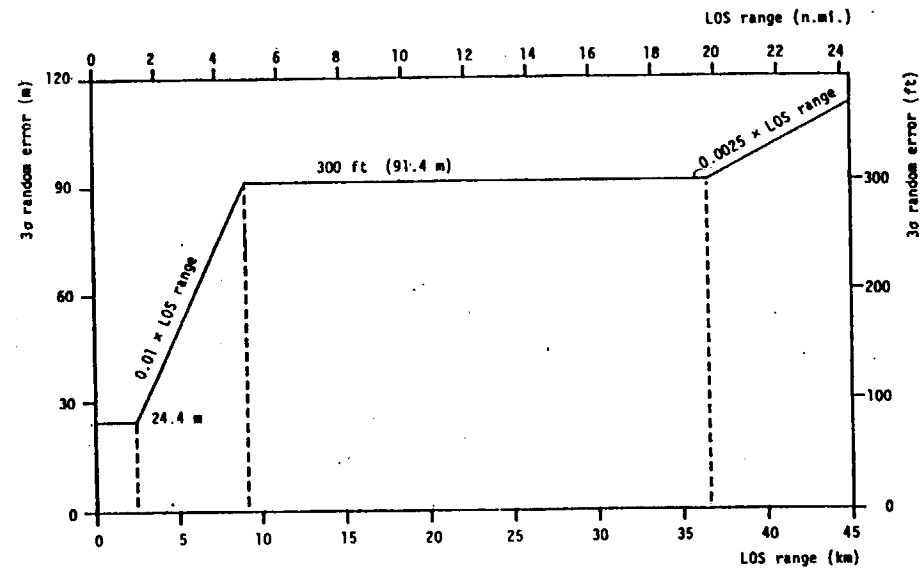
b. Angle measurements capability shall be maintained over the full coverage capability of the antenna with accuracy degraded to levels no less than the equivalent of communication angle measurement accuracy.

RADAR PARAMETER ALLOWABLE MEASUREMENT ERRORS

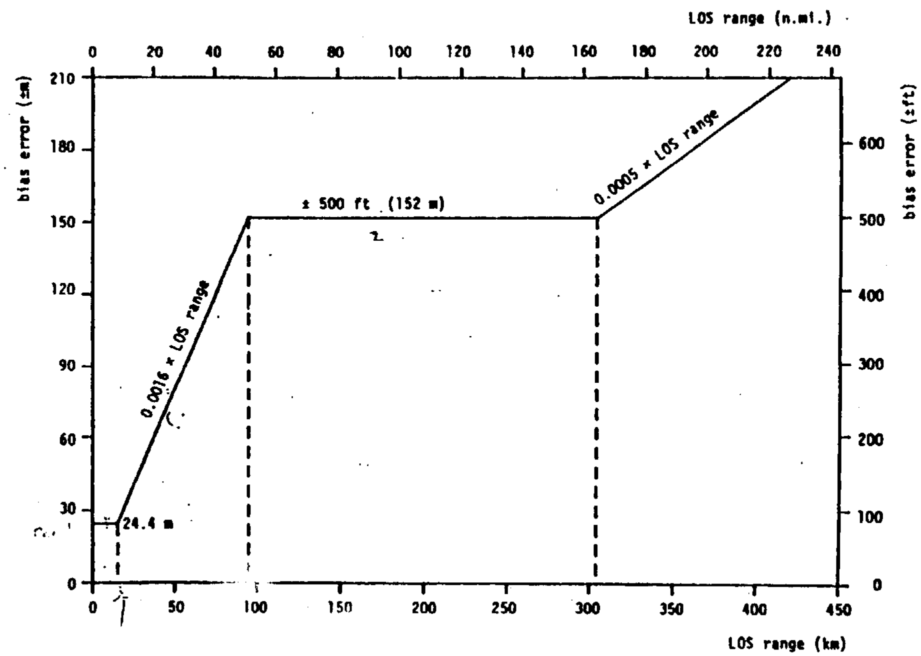
PARAMETER	RANDOM ERROR	ACTIVE MODE
LOS range	a	c
LOS range	1 ft/s (0.3 m/s) or 1 percent of range rate, whichever is greater	±1 ft/s (0.3 m/s)
LOS pitch angle	8 mrad (0.458 deg)	±3 deg[d]
LOS roll angle	8 mrad (0.458 deg)	±3 deg[d]
Pitch inertial angle rate[b]	0.14 mrad/s (0.008 deg/s)	+0.14 mrad/s (0.008 deg/s)
Roll inertial angle rate[b]	0.14 mrad/s (0.008 deg/s)	±0.14 mrad/s (0.008 deg/s)

[a]See 3σ range range error chart
[b]Not including target effects
[c]See range bias error chart
[d]Include 2 deg requirement value plus a structural uncertainty of 1 deg

3σ RANDOM RANGE ERROR



RANGE BIAS ERROR



REQUIREMENTS ON MEASUREMENT INTERVALS

- Measurement interval considerations may be important for passive optical of tracking of the target due to possible lighting constraint requirements
- Optical tracking performance versus number and placement of measurements in the track arc
  - — Targeting solution converges after 15 minutes
  - — Any 15 minute track period within the total track period is satisfactory
    - Smoothing is not as important due to high quality sensor but still need 15 minutes of geometry change over the arc
  - — Measurements need not be continuous as long as they span the 15 minute arc. Last set of marks should be taken as close to a maneuver as possible
  - — Crosstrack nav errors converge in about four minutes if track is initiated on position error peak, and six minutes if at a position error null

REQUIREMENTS ON MEASUREMENT INTERVALS (cont'd)

- For radar operation, tracking is continuous in a track interval, until sensor breaks lock due to attitude constraints or a maneuver occurs
  - — Filter state convergence typically occurs in 15 minutes (includes angle bias estimation)
    - Fifteen minute track period provides needed geometry change
  - — Would like continuous radar track in order to smooth the large radar random errors

- It is desirable to track as close as possible to an upcoming targeted maneuver to keep state error propagation to a minimum. This is especially important if large target errors exist and the active vehicle state is the only state updated in the filter

FILTER DESIGN/OPERATION

- Rendezvous nav filters to date have updated only one vehicle state in filter formulation
  - — Non-updated vehicle state is assumed to be "perfect"
    - This has worked well since, in most rendezvous cases, the target state has been accurately known
    - Provision is usually made to update the state which is known a-priori to have the largest ephemeris error
    - For the case in which the non-updated state error is very large, star tracker "angle only" navigation is more effective than range plus star tracker angles
      - With no direct measurement of range, the filter can absorb the effect of the non-updated state errors in the state error along the LOS. This extra degree of freedom allows the line of sight rate residual to be driven to zero so that the relative state propagates better.
    - Including both vehicle states in the filter design eliminates all of these considerations. Both vehicle states are adjusted so that relative state propagation is much improved.

FILTER DESIGN/OPERATIONS (cont'd)

- Rendezvous sensor biases are estimated in the filter
  - — Effective* angle biases: unobservable unless range and angle measurement combination is used; out-of-plane effective angle bias is observable if track arc is long enough
  - — Range rate: fairly observable with range and range rate measurements (range helps converge bias estimate more rapidly)
  - — Range bias: typically unobservable

- Includes:
  - Sensor angle biases
  - platform misalignment
  - sensor mounting error

INITIALIZING FILTER COVARIANCE MATRIX

- If a six state filter is used (i.e., only one vehicle state is estimated) the covariance matrix represents relative state errors and not inertial vehicle state errors. Typically, the target and active vehicle a priori error covariance matrices are RSS'd to obtain the desired relative covariance matrix

- Despite the fact that angle biases are unobservable, except with range measurements, an update to the bias estimate from the initial measurement residuals will be made with angle only tracking, depending on how the initial filter covariance loads apportion the error between the state and biases
  - — Typically, the filter is designed for a degradation in state error rather than a degradation in sensor bias
  - — Consequently, the state portion of the covariance is loaded conservatively to reduce bias estimation initially

- Obviously if the bias is observable, the filter continues to update the bias estimates

PROCESS NOISE

- Usually used to compensate for unmodeled errors such as gravity, drag, algorithm errors, etc.

- Apollo, using a square root filter formulation, did not use process noise due to the mathematical complexity involved. Instead the filter covariance was periodically reinitialized (i.e., limited memory filter)

- Shuttle on-orbit filter includes three unmodeled acceleration states which effectively act like process noise.
  - State process noise is also added during powered phase of the on-orbit filter.

BIAS MODELING

- All biases in Shuttle on orbit filter are modeled as exponentially correlated random variables (ECRV's)
  - In the filter covariance matrix, the bias is exponentially decayed during propagation with process noise added each timestep
  - For the actual bias estimation, exponential decay is eliminated during propagation
  - This allows a great deal of flexibility in estimating many types of bias behavior
    - Constants
    - Ramps
    - Sinusoids
  - The ECRV's use a time constant and variance which depend on the various types of biases to be estimated

GUIDANCE/TARGETING AND TRAJECTORY DESIGN

- **Profile design considerations**
  - — Sensor constraints
    - Critical on-board targeted maneuvers must be designed to be within sensor acquisition range with a pre-maneuver tracking period to support maneuver targeting
    - To facilitate target acquisition, search volume can be minimized and acquisition time can be lengthened by appropriate trajectory design (e.g., coelliptic approach)
    - Profile must be designed to accommodate unique tracking requirements of each sensor
      - e.g., reflected sunlight must be available with adequate tracking time before each maneuver for star tracker navigation (assumes non-cooperative target)

CSDL

GUIDANCE/TARGETING AND TRAJECTORY DESIGN (cont'd)

- Profile trajectory characteristics must accommodate sensor tracking constraints

  (e.g., max. range, rate, angle rate limits)

- Depending on sensor accuracies, sufficient tracking time must be provided before on board targeted maneuvers, to accurately target such maneuvers
  - — Large sensor random errors require smoothing
  - — Large observable biases require time to adequately estimate such bias effects

- If possible, profile should be designed to maintain relative sensor lock on throughout the terminal phase of rendezvous

CSDL

GUIDANCE/TARGETING AND TRAJECTORY DESIGN (cont'd)

- Profile design considerations (cont'd)
  - — Dispersion handing capability
    - Would like profiles to be relatively insensitive to dispersions, e.g.,
      - MRSR direct ascent would have smaller dispersions at circularization due to shorter transfer time than Hohmann ascent
      - coelliptic altitude difference must be large enough to maintain a positive closing rate, despite dispersions, and yet small enough to maximize acquisition time
    - Profile should handle as broad a spectrum of dispersions as possible while still maintaining integrity of desired profile characteristics, e.g.
      - use of elevation angle to specify maneuver time to maintain "standard" closing profile to VBAR offset in presence of trajectory dispersions
      - design trajectory to have multiple rendezvous opportunities to handle contingency cases

GUIDANCE/TARGETING AND TRAJECTORY DESIGN (cont'd)

- — Consideration should be given in maneuver sequence planning to resolve crosstrack dispersions
  - In an efficient manner (RSS them with other large rendezvous maneuvers)
  - Prior to arrival at prox ops region (facilitates mission planning, procedures development and prox ops performance)
- — Maneuvers should be "biased" so that smallest deltaV penalty above the theoretical optimum is achieved
- — If active vehicle performs rendezvous from below, dispersions are handled without need for retrograde maneuver which would further reduce relative perigee
  - Similarly, if active vehicle performs rendezvous from above, dispersions are handled with no posigrade maneuvers which would increase the relative apogee
- — Maneuvers should not be trimmed lower than the nav uncertainty in targeting that maneuver

GUIDANCE/TARGETING AND TRAJECTORY DESIGN (cont'd)

- Targeting
  - — On-board targeting capability should permit the targeting of all maneuvers by the IGN&C system
    - Maximize autonomous AR&D capability
    - Utilizes the onboard maintenance and updating of the relative state

GUIDANCE/TARGETING AND TRAJECTORY DESIGN (cont'd)

- IMU Considerations
  - — Shuttle quality IMU is adequate for sensing translational maneuvers
    - Use of flight control system indicators of reaction control system jet firings appropriately set the guidance and navigation IMU velocity change thresholds. This permits incorporation of IMU readings into the guidance and nav state for translational maneuver executions
    - IMU velocity change thresholds are used to prevent incorporation of IMU acceleration biases into the navigation state when no translateral velocity change is being imparted to the vehicle CG.

GUIDANCE/TARGETING AND TRAJECTORY DESIGN (cont'd)

- Translation Maneuver Execution Guidance
  - — Guidance capabilities should be able to handle the following:
    - Execute maneuvers along the velocity-to-be gained (VGO) vector for fixed inertial direction as well as guided burns (VGO continuously changing direction), of arbitrary duration
    - Axis by axis thrusting capability for small translational maneuvers is necessary
  - — Low thrust guidance must be able to partition over several revolutions, the inplane velocity correction combined with the out-of-plane correction, executed within a given angle of the active and target vehicle orbit plane crossings
  - — IMU sensed velocity change can be used by this guidance algorithm depending on the accuracy of the IMU and the size of the translational maneuvers being executed
  - — An "automatic" low thrust maneuver execution capability, independent of IMU velocity change sensing quality, can be achieved by modeling the accelerations of the thruster configurations on the vehicle

CONTROL SYSTEM

- FCS which considers translation and rotation separately is a proven technique for handling the rendezvous mission phase
- Current shuttle type DAP is adequate for relative tracking and attitude maneuver execution
  - — Phase Plane for determining attitude control RCS firings
  - — Table lookup Jet Select Logic
- Effect of vehicle attitude control effectors on trajectory must be considered
  - — Coupled moments versus cross-coupling of translation/rotation
- FCS indications of RCS jet firings to both the nav and guidance systems permits the use of IMU velocity change thresholds to:
  - — allow sensing of translational effects resulting from rotational maneuvers
  - — permit incorporation of small RCS translational firings

PROXIMITY OPERATIONS PHASE

GENERAL COMMENTS

- Proximity operations, from the final rendezvous midcourse correction to docking, consists essentially of two subphases:
  - From final midcourse to VBAR stationkeeping offset or VBAR crossing relative to the target
    - System can null relative velocity if conditions warrant
  - An approach phase from VBAR stationkeeping offset or VBAR crossing to docking

IGN&C SYSTEMS CONSIDERATIONS

- Requirements on accuracy of maintaining position, velocity and attitude of active vehicle relative to the target increases as the range to the target decreases
- System must be able to reconfigure rapidly in response to system failures or target motion
- May be desirable to enable integrated system to follow an arbitrary approach trajectory rather than pre-planned approach path
- Appropriate level of fault tolerance is required
  — Fail/Safe
- Minimize plane impingement and contamination of the target
- Docking conditions within the docking mechanism constraints must be achieved independent of approach path initial conditions and system failures

IGN&C SYSTEM CONSIDERATIONS (cont'd)

- GN&C subsystem design must occur in context of Integrated GN&C system development
- Small translational maneuver execution capability is mandatory
- "Standard" IGN&C system operations may adversely affect IGN&C system performance, necessitating departure from "standard" operations
- In the phased evolution of an ARAD system, the distinction between guidance, navigation and control disciplines as "separate" but integrated will evolve into an integrated system developed at the design level
- Combined rotational and translational control would provide increased operational flexibility and possible performance improvement
  - Current IGN&C system development separates attitude (rotational) control and translational control
  - Control system and guidance system responsibilities
- Ability to perform translation of and rotation about arbitrary points relative to the vehicle would provide additional performance benefits

NAVIGATION

- Higher accuracy in the estimation of the relative state (position, velocity, attitude) is required
  - Angles only measurements are not adequate all the way to docking because error resolution along the line ght is poor
  - Rendezvous radar is not adequate all the way to docking because of
    - Large measurement errors in range and angles
    - A large range bias which is unobservable
  - Consequently, a high accuracy LASER sensor that measures range and line of sight angles with negligible measurement biases, is required
  - It is possible that a properly mechanized GPS nav system on each vehicle may be adequate to resolve the relative problem to some TBD relative range, but not to effect an acceptable docking condition

TARGET ATTITUDE

- In proximity operations phase, achievement of required state accuracy is not possible without information about target attitude
  - Knowledge of target attitude is not important for the rendezvous phase except near prox ops transition with a large target
- Relative attitude information is required for
  - Precise knowledge of reflector location for navigation
  - Alignment of docking ports
  - Collision avoidance
- Relative Attitude can be determined by:
  - transfer of target inertial attitude information from the target
  - estimation of target attitude by the active vehicle, using measurements from prox ops sensor

LASER SENSOR ACCURACY

- JSC Communication and Tracking Division LASER sensor specification adequate to provide required nav accuracy (with appropriate nav system configuration)
- The following are the JSC LASER sensor specifications

LASER DOCKING SENSOR ACCURACY

1σ ERROR		SYSTEM RANGE					
		0.1 ft	100 ft	1,000 ft	3,280 ft	12,000 ft	22,000 ft
Range (ft)	Specification	0.016	1	10	32.8	120	220
Range Rate (ft/s)	Specification	0.01	0.032	0.07	0.104	0.16	0.196
Bearing (deg)	Specification	0.65	0.065	0.03	0.05	0.05	0.05
Bearing Rate (deg/s)	Specification	0.537	0.017	0.0054	0.003	0.003	0.003
Pitch, Yaw (deg)	Specification	0.3	0.3				
Pitch, Yaw Rate (deg/s)	Specification	0.01	0.1				
Roll (deg)	Specification	0.3	0.3				
Roll (deg/s)	Specification	0.01	0.01				

Physical:	Size	Weight	Input Power
Specification:	1 ft^3	50 lbs	75 Watts
Capability:	16"×16"×6.75" (1 ft^3)	36 lbs	58.8 Watts

LASER SENSOR ACCURACY (cont'd)

- Navigation tracking intervals
  - It is important to maintain continuous tracking during the prox ops interval
  - Errors in sensing C.G. translation from the frequent maneuvers (both rotational and translational), as well as plume impingement effects, will cause relative state degradation and must be resolved immediately
  - In general, tracking is not required during maneuver execution
    - However, if estimation of accelerometer bias is required to maintain accuracy of relative state estimates, navigation must be continuous throughout the burn

FILTER/DESIGN OPERATIONS

- Because of the higher accuracy required, errors previously considered negligible for rendezvous are important considerations in prox ops,
  - — e.g.,
    - position error occuring from assumption of constant acceleration for sensed translational ΔV over the nav cycl while on the order of only a few feet, must be resolved quickly
      - Laser sensor is so accurate that in steady state, negligible measurement residuals are expected
      - If residual occurs, it is assumed to be caused by velc error and an erroneous state update occurs
    - Fix:
      - Position process noise is added to filter covariance when RCS jets are fired over the nav cycle, to prevent editing of subsequent marks
      - In addition, velocity updating is downweighted, thereby preventing large velocity transients

FILTER DESIGN/OPERATIONS (cont'd)

- Errors in sensing the maneuvers must be resolved more rapidly due to close ranges involved and the need to maintain tighter trajectory control
  - — Three options can be considered for measuring the effect of the maneuver on the relative state
    - Sense the maneuver using the IMU and provide added compensation in the filter to model the effect of accelerometer bias which is more pronounced due to the greater number of burns
      - Estimate accelerometer bias
      - Increase the unmodeled acceleration variance (process noise)
    - Don't sense the maneuvers. Utilize prox ops sensor to resolve maneuver execution errors
    - Estimate acceleration by modeling the jet firings

FILTER DESIGN/OPERATION (cont'd)

- From the nav standpoint, results to date indicate either of these approaches will work.

  However, the approach of continuous sensing of maneuvers to cover such contingencies as stuck jets and resolution of large maneuver ΔV's is recommended.

RELATIVE ATTITUDE FILTER

- Two approaches can be used to determine relative attitude between the vehicles
  - — Assumption is that the LASER prox ops sensor is tracking three reflectors at a known location on the target and in a known geometrical configuration

    1) Prox ops sensor measures relative attitude directly
       - Range measurements to the three reflectors are differenced for relative pitch and yaw, and polarization of reflected return is utilized for roll

    2) Calculation of relative attitude from measurements

       LASER sequentially tracks each reflector. The resulting range vector to each reflector (range magnitudes and angles) is utilized to determine the target relative attitude
       - A more accurate relative attitude can be achieved if the measurements are processed in a Kalman filter rather than using a deterministic solution
       - In the LASER system studied it was necessary to determine which reflector was being tracked. A problem here was that the measurement accuracy required for reflector identification was higher than the accuracy required for effective attitude determination.
       - However in all cases, identification occured at ranges that were on the order of several hundred feet from the target

TRAJECTORY DESIGN

- Standardization of approach trajectory can reduce requirements on target attitude control for cooperative targets
- Profile design and vehicle approach attitude must take into account active vehicle control characteristics
  - Rotational/translational cross coupling
  - Attitude and attitude rate deadbands
  - Minimum impulse on RCS jets used for translational maneuvers
- Approach profile and IGN&C system operation should
  - Minimize plume impingement and contamination of the target thereby minimizing also, the effect of subsequent target rotation and translation on AR&D system performance
  - Utilize orbital mechanics effects if possible

TRAJECTORY DESIGN (cont'd)

- From last midcourse to VBAR stationkeeping
  - Profiles are usually determined by rendezvous phase trajectory or by ascent trajectory if a direct insertion ascent is flown (e.g., MRSR)
  - Maneuvers will be executed as required to place the vehicle on an intercept with VBAR stationkeeping/ crossing point
    - Standard midcourse type maneuvers
    - Braking and line-of-sight control maneuvers implemented using Lambert calculations with time-of-flight adjustments
      - This combines braking maneuvers with line-of-sight control
  - Relative velocity null maneuver can be performed if required to maintain position on VBAR

TRAJECTORY DESIGN (cont'd)

- Approach from VBAR stationkeeping offset (or crossing) to docking
  - — Profile design has a much stronger influence on IGN&C system performance than in the previous mission phases
    - Tighter trajectory requirements, i.e., "corridors" that decrease with range to docking port, impose:
      - Stringent navigation requirements on the IGN&C system to permit targeting of maneuvers to maintain vehicle within the corridor
      - This will in turn impose requirements on the system procedures, e.g., the sensor must be able to track the reflectors with no help from vehicle attitude maneuvers, while vehicle is maintaining attitude parallel to docking port during the approach.
      - Speed of response required and the desire to limit attitude maneuvers preclude the vehicle from aiding sensor tracking of the target

TRAJECTORY DESIGN (cont'd)

- Approach from VBAR stationkeeping offset (or crossing) to docking (cont'd)
  - — Considerations such as the one above must be factored into the overall trajectory design

    e.g., if docking port is out-of-plane, the desired in-plane approach may have to be appropriately modified
    - For relative attitude estimation, better accuracy is attained from straight in approach to the reflector set than a side angle approach
- Profile should be designed to handle:
  - — Reasonable initial VBAR dispersions
  - — Reasonable initial state errors
  - — Degraded sensor performance
- Profile should provide stable recovery points which permit
  - — Termination of approach phase for system failure assessment
  - — Re-establishment of approach to docking trajectory

GUIDANCE/TARGETING

- The guidance/targeting scheme selected to fly the desired profile can impose additional demands on the navigation system

  e.g., Linear quadratic regulator design requires many small maneuvers since it is controlling vehicle about a desired reference set point

  — These maneuvers require sensing by IMU with attendent accelerometer bias, or they impose a requirement of a highly accurate prox ops sensor to measure the resulting state change

- The number of required maneuvers can be reduced, fuel usage can be reduced, and closing rates easily controlled by designing a profile and guidance scheme which utilizes effects of orbital mechanics and does not continuously control the profile in all dimensions about a set point

GUIDANCE/TARGETING (cont'd)

- Use of guidance schemes which have been developed for "manual" operations

  — If the guidance technique has been designed for crew monitoring without computer displays, (line-of-sight control independent of range rate control, e.g., optimal VBAR), they usually have higher fuel costs and do not account for orbital mechanics effects

  — They utilize crew learning through simulations to obtain (optimize) desired performance

  — If these designs are to be used in an automatic system:

  1) orbital mechanic effects can be utilized, and
  2) effect of "crew learning" though repeated simulations must be appropriately incorporated into guidance algorithms to achieve desired performance

     e.g - for the guided VBAR guidance and targeting scheme, code has to be modified to prohibit maneuver execution near cusp retarget point which will impinge target

     - Maintain desired minimum closing rate throughout the profile (i.e., no stall)

GUIDANCE/TARGETING (cont'd)

- Translational Maneuver Execution
  - — Use IMU ΔV feedback to guidance if burn can be accurately sensed by the IMU
    - Thrust level relative to IMU errors
  - — Perform the maneuver "open loop" by modeling the RCS jets thrust direction and magnitudes, if the maneuver Δ is below the level of being accurately measured by the IMU
    - Maneuver effect on nav state is subsequently resolved by prox ops sensor measurements and the navigation system
    - IMU accelerometer bias does not affect burn execution

CONTROL

- In work performed to date, a shuttle type FCS which controls rotation independent of translation is adequate for an initial phase AR&D system

- Automatic moding of reaction jet capability, such as switching from primary to vernier jets for attitude control as well as translation maneuver execution, must be embedded in control system design

- Automatic execution of translational maneuvers is accomplished as discussed earlier, by using a shuttle FCS type translation pulse mode capability, where the maneuver algorithm determines the length of time to fire the appropriate translational control jets depending on minimum impulse of the jets
  - — Replaces manual execution of RCS translation burns
  - — Note that this is open loop and the accuracy of the burn execution is dependent on the modeling of the RCS translation forces
  - — If available, a high quality IMU with small acceleration biases could be used to sense the maneuvers and provide a closed loop guidance capability

CONTROL (cont'd)

- Thruster location effects
  - — Location of thrusters can produce highly coupled rotation and translation of the vehicle center of mass
  - — These effects can be mitigated by use of IMU during rotation to sense the imparted translational ΔV (as currently down on the Shuttle)
  - — An alternate method is to model jet thrust direction and magnitude in the system
  - — An optimal jet select logic in the control algorithm would enable the selection of jets for rotation which would minimize cross coupling
- Controlling, rotation about the vehicle CM will provide docking port translation relative to the target
  - — Implementation of an offset point control capability in the AR&D system will mitigate this effect
  - — This requires a jet select algorithm which takes into account desired rotation and translational acceleration of the CM

CONTROL (cont'd)

- Rotation/Translation coupling
  - — Optimal 6-DOF jet select with off-set point control
    - For translation commands, fuel optimal 6-DOF solution allows translation of the docking mechanism with minimal cross-coupling effects
    - With Off-Set Point Control, combined translation and rotation cmds about the c.g. produce pure rotations about the docking mechanism with minimal off-axis errors
  - — A smaller minimum impulse size will also reduce the cross-coupling rates built up over a minimum impulse firing
- Translation pulse size
  - — Current translation pulse size limits the docking contact conditions
  - — Translation pulse size can be reduced by the following:
    - Provide capability for on-orbit DAP to command small minimum impulse jet firings (current Shuttle min on-time is 80 msec)
      - Add vernier jet thrusters translation capability

CONTROL (cont'd)

- **Minimization of plume impingement**
  - — Depending on vehicle thruster configuration, pluming of the target may be difficult to avoid. A dynamic reconfiguration of the control thrusters could be used to minimize pluming of the target. This requires a model of the plume regions and the target vehicle geometry. The thrusters used to control the vehicle are dynamically reconfigured to avoid pluming the target

CSDL

CANDIDATE DESIGN

AR&D IGN&C SYSTEM

- Attributes of an "ideal" AR&D system
  - Sensor complement to accurately determine relative position and velocity, and attitude at close ranges
  - Effectors to provide range of translational and attitude maneuver capability
  - Control of either the 6-DOF intertial state or the 6-DOF relative state
  - Rapid reconfiguration in response to system failures or target motion
  - Appropriate level of fault tolerance (at lease Fail/OP)
  - Flexible enough to follow an arbitrary approach trajectory
  - Linear actuators with small minimum impulse size for precise control
  - Thrusters which point away from the target vehicle to minimize propulsive pluming
  - Neutral thrusters to avoid residual contamination
  - Robust mission supervisor (operations manager)
- The demands on the system increase as the range to the target decreases
  - Relatively coarse maintenance of relative position and attitude required for rendezvous
  - Very precise state maintenance required for Docking

USE OF SHUTTLE TYPE IGN&C SYSTEM REQUIREMENTS AS A BASE FOR A PHASED AR&D SYSTEM DESIGN APPROACH

- Discussion
  - The candidate design outlined on the following charts presents a system design based on current shuttle IGN&C system requirements with those additions necessary to provide a first phase AR&D system capability
    - As performance analysis of this system dictates, modification to the integrated system would be made to refine system performance to provide:
      - Improved docking conditions (reduced contact rates and smaller docking port misalignments)
      - Multiple docking attempt capability
      - Lower plume-impingent on and contamination of the target
      - Robust performance in the presence of system failures
      - Fail safe operation capability
      - Comprehensive mission supervisor

USE OF SHUTTLE TYPE IGN&C SYSTEM REQUIREMENTS AS THE BASE FOR A PHASED ARAD SYSTEM DESIGN APPROACH (cont'd)

- In general:
  - Shuttle IGN&C system hardware and software performs satisfactorily for rendezvous but not Prox Ops and docking
  - Actions can be made autonomous by automating crew procedures for Rendezvous
  - System modifications are required for autonomous Prox Ops and Docking
  - IGN&C AR&D system must be designed as an iterative process with the navigation, guidance/targeting and control system design
- Using shuttle hardware for autonomous prox ops and docking presents a challenge and thus represents a good test case
- The shuttle system deficiencies can be eliminated by means of phased software upgrades as dictated by performance analysis results
  - Docking mechanism capabilities dictate docking condition requirements, for example

SHUTTLE DEFICIENCIES FOR PROX OPS

- Rendezvous radar does not provide valid measurements at ranges less than 100 ft
- Thrusters are poorly placed, causing highly coupled rotation and translation
- Coarseness of translation minimized impulse limits docking conditions that can be achieved
- Significant pluming of the target is minimized only through proper choice of approach trajectory to the docking port
- No software, to precisely maintain relative profile during prox ops phase
- No direct control of docking port, only of orbiter CG
- Rapid reconfiguration of the IGN&C system does not exist
- Lack of Mission supervisor for autonomous operations of IGN&C system
  - IGN&C operations and procedures under crew or ground control

Autonomous AR&D IGN&C System Development

Proximity Operations Mission Phase

System Attributes	Desired	Shuttle Type System Capabilities	Phased Enhancements
a Accurate targeting of maneuvers required to continously maintain desired approach path	- Maneuver targeting error is considerably less than the velocity change required to maintain the vehicle within the corridor limits about the reference profile . Maneuver requirements can be on the order of 0.04 fps to maintain precise profile during approach to docking	- Targeting error using the shuttle radar is slightly more than the RCS minimum impulse translation capability . On the order of .04 fps to .08 fps depending on axis	- Use of Laser sensor for navigation enables the targeting of maneuvers to the required accuracy
b Sensor complement (for relative navigation and sensing of rotation and translation) with the necessary accuracy	- Prox ops sensor with small random and bias sensor errors . Small bias errors solves non-observability and bias estimation problems	- Radar range bias of 26 ft. is not estimated by the filter - RR minimum range of 100 ft precludes its use as a proximity operations sensor - Shuttle quality IMU provides acceptable performance for Prox Ops	- Add Laser sensor
c Maintains accurate det[illegible] of relative states: - Position - Velocity - Attitude - Attitude rate	- Continuous relative state estimation, accurately maintained in this phase. . During active vehicle coast, attitude maneuvers and translational maneuvers . During rapid relative motion changes induced by plume impingement	- Current radar sensor and nav filter configuration provides required accuracies for operations to the radar minimum range limit of 100 ft.	- Processing of Laser measurements in the nav filter for relative position and velocity with the necessary filter modifications - Use of Laser measurements in attitude Kalman filter to provide relative attitude estimates - Requires reflector triad on the target in known location
d. Relative state maintainance - Position - Velocity - Attitude - Attitude rate	- Relative position and velocity maintained continously within desired limits about the reference profile. . Dispersion limits are dependent on the profile design - Combined relative position, velocity and attitude continuously maintained as rauired by the profile design	- Relative position and velocity maintained manually . Translation maneuvers executed as required - Relative postion and velocity maintained separately from relative attitude control	- Trajectory controller for relative positon and velocity - Linear quadratic - Guided VBAR - Relative attitude control can be achieved by using outputs from esimator to null relative attitude error

Autonomous AR&D IGN&C System Development

Proximity Operations Mission Phase

System Attributes	Desired	Shuttle Type System Capabilities	Phased Enhancements
d Relative state maintainence (continued)	- Minimize rotational/translational cross coupling - Control of rotation and translation about points other than the active vehicle center of mass - Cooperative control	- Strongly coupled rotation and translation - Proposed software upgrades will reduce the crosscoupling . Reduce minimum firing time	- Use of current Shuttle FCS requirements provides acceptable performance for initial AR&D system operation - 6 DOF jet select
e Translational maneuver execution	- Execute translational maneuvers with: . Wide range of magnitudes . Small maneuver execution errors . Small maneuver residuals	- Shuttle provides automatic translation capability for OMS maneuvers - Powered flight guidance can execute inertially fixed burns and Lambert guided burns - RCS translation maneuvers, for small deltav, are executed manually	- Provide an automatic capability to execute RCS translation maneuvers, both axis-by-axis and along the velocity-to-be-gained - Automatic upmoding to PRCS for translation manuevers and downmoding to VRCS, if required, following the maneuver
f Effector capabilities	- Translation: . Throttlable . Maximum values as required by the profiles . Minimun value of .01 fps - Rotation: . From 1.0 to .01 deg/sec . Accurate to .01 deg/sec	- Translation: . Bang-bang . Minimum tranlation impulse of .04 fps to .08 depending on body axis direction - Rotation: . From 2 to .01 deg/sec . Accurate to .01 deg/sec	- None required - None required Reduction in minimum [illegible] on time would improve [illegible]apability
g. Plume impingement and contamination of the target	- Minimize plume impingment and contamination using . Cold gas RCS jets . Plume direction away from the target	- Minimized by manual operations using: . Low-Z jets (reduces control authority) . Approach profile design	- Trajectory controller for an approach which minimizes impingment and contamination - Dynamic plume avoidance by appropriate jet select algorith modifications
h. Collision avoidance	- "Zero" possibility of catastrophic collision - Able to handle variety of complex target configurations	- Manual operations reduce risk of collision to near "zero"	- None required for initial AR&D system approaching cooperative targets of known configuration

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Autonomous AR&D IGN&C System Development

Rendezvous Mission Phase

System Attributes	Desired	Shuttle Type System Capabilities	Phased Enhancements
a Accurate targeting of rendezvous maneuvers required by the mission design	- Maneuver targeting error decreases with aproach to Prox Ops phase takeover - Size of maneuver error acceptable is dependent on rendezvous profile chosen	- Targeting error accuracies with shuttle system performance are acceptable for AR&D mission profiles considered to date - Lambert targeting capability only	- None required - Incorporation of general maneuver targeting capability (GMP) with finite/low thrust modifications would increase autonomy
b Sensor complement (for relative navigation and sensing of rotation and translation) with the necessary accuracy	- High accuracy angle measurements at large relative range - Addition of range measurements at close range to reduce size of final dispersion ellipse	- Shuttle navigation sensor complement provides acceptable measurements quality for rendezvous mission phase - Star Tracker utilizing reflected sun from the target - Rendezvous Radar with 20 nm. skin track range of target - Gimballed IMU for sensing rotation and acceleration	- None required - Improvement in accuracy of radar and IMU would provide improvement in system performance
c Maintains accurate estimates of the inertial and/or relative states of the chaser and target vehicle - Position - Velocity	- Inertial and relative states maintained with the component accuracies and correlations for accurate maneuver targeting - Relative nav accuracy independent of inertial state error size at the start of rendezvous	- Shuttle nav filter configuration provides the desired state estimation accurace for "reasonable" inertial error size of the non-updated vehicle state - Filter implementation assumes the inertial errors of the non-updated vehicle are "small", on the order of 10 nm or less	- None required for reasonable inertial errors of the non-updated vehicle - Augmentation of the filter would provide improved system performance for a larger set of inertial state errors at the start of rendezvous
d Active vehicle state maintenance - Position and Velocity Attitude and attitude rate	- Position and Velocity. . Maintained in "proximity" of desired nominal profile Profile design may require the active vehicle to achieve a desired relative offset	- Velocity corrections executed at discrete points specified in mission timeline to achieve either desired orbit conditions or desired offset relative to the target	- None required
	- Attitude control about the center of mass Accurate enough for IMU alignment, sensor acquisition and target track, translational maneuver execution	- Attitude control accuracy adequate for all rendezvous requirements including OMS TVC maneuvers and RCS translational maneuvers	- None required
	- No rotational/translational cross coupling	- Strong rotational/translational cross coupling	

Autonomous AR&D IGN&C System Development

Rendezvous Mission Phase

System Attributes	Desired	Shuttle Type System Capabilities	Phased Enhancements
e. Translational maneuver execution	- Execute translational maneuvers with: . Wide range of magnitudes . Small maneuver execution errors . Small maneuver residuals	- Shuttle provides automatic translation capability for OMS maneuvers - Powered flight guidance can execute inertially fixed burns and Lambert guided burns - RCS translation maneuvers, for small deltav, are executed manually	- Provide an automatic capability to execute RCS translation maneuvers, both axis-by-axis and along the velocity-to-be-gained - Automatic upmoding to PRCS for translation maneuvers and downmoding to VRCS, if required, following the maneuver
f Attitude maneuver execution	- Provide no translational cross-coupling: pure rotation about the center of mass	- Strong cross-coupling between rotation and translation	- None required Optimum jet select would would reduce crosscoupling
	- Capability for range of attitude maneuver rates and for range of attitude and attitude rate deadbands	- FCS jet select algorithm uses: . Attitude and attitude rate phase planes . Table lookup jet select	- None required
g. Effector capabilities	- Translation: . Capability to execute large range of maneuver leves	- Shuttle OMS capabilities and RCS translation capabilities provide adequate deltav range to accomplish rendezvous	- None required
	- Rotation: . No rotational/translational cross coupling	- Strong rotational/translational cross coupling	- None required

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RENDEZVOUS PHASE CANDIDATE DESIGN

- Current Shuttle IGN&C system requirements will provide satisfactory performance for automatic rendezvous operations with relatively few modifications:
  - — Automatic axis-by-axis RCS translation capability for executing RCS maneuvers
  - — Automating crew and mission operations GN&C procedures to replace manual and ground controlled system inputs
    - e.g.:
      - nav sensor selection
      - PRCS/VRCS selection
  - — Augmentation of Shuttle on-board targeting program to include maneuver targeting capability similar to the MOD orbital maneuver processor (OMP) with finite/low thrust capabilities. Provides increased flexibility and autonomy in the rendezvous profile to be flown
- Sensor complement of Shuttle quality provides satisfactory navigation accuracy
  - — Star tracker
  - — Radar
  - — IMU
- Shuttle effectors (OMS, PRCS, VRCS) are well suited for this mission phase
- Proper choice and design of rendezvous profile will maximize dispersion handling capability and provide maximum use of onboard IGN&C systems capability

PROXIMITY OPERATIONS PHASE CANDIDATE DESIGN

- Shuttle IGN&C system requirements with the following upgrades will provide on initial candidate automatic prox ops system
  - — Software:
    - automatic RCS translation maneuver capability
    - Laser nav tracking capability
    - Proximity operations trajectory controller
  - — Automated procedures and mission operations
- Addition of a relative navigation proximity operations sensor, with JSC command Track LASER specifications shown earlier, will provide the required navigation accuracy for the system
- Initial studies have demonstrated acceptable profile performance for:
  - — Guided VBAR trajectory controller
  - — Linear quadratic regulator following a linear VBAR approach trajectory between desired relative offset conditions

— Plume impingement on target is minimized by choice of approach targeting

A PHASED APPROACH TO THE DEVELOPMENT OF AN INTEGRATED GUIDANCE, NAVIGATION AND CONTROL SYSTEM FOR AUTONOMOUS RENDEZVOUS AND DOCKING

PERFORMANCE ANALYSIS OF A CANDIDATE AR&D SYSTEM DESIGN

CSDL AR&D WORKING GROUP

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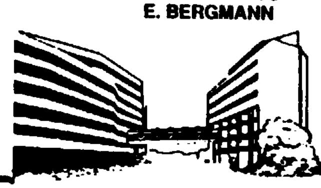
THE CHARLES STARK DRAPER LABORATORY, INC.



OUTLINE

- Performance Analysis Overview
  - Analysis Objectives / Approach
  - System Developments
  - Performance Analysis Data Base (Software / Hardware)
  - AR&D system analysis simulations
- Rendezvous Performance
  - Figures of Merit
  - Performance Analysis summary for:
    - Earth Operations
    - Mars Operations
- Proximity Operations Performance
  - Analysis areas
  - Figures of Merit
  - Proximity Operations Profile Discussion
  - Results
    - Summary of navigation performance studies evaluating the use of a laser sensor for
      - Relative Attitude
      - Relative State Navigation
    - VBAR Approach using Linear Quadratic Regulator
    - "Guided" VBAR Approach
- Summary

PERFORMANCE ANALYSIS OVERVIEW

OBJECTIVES:

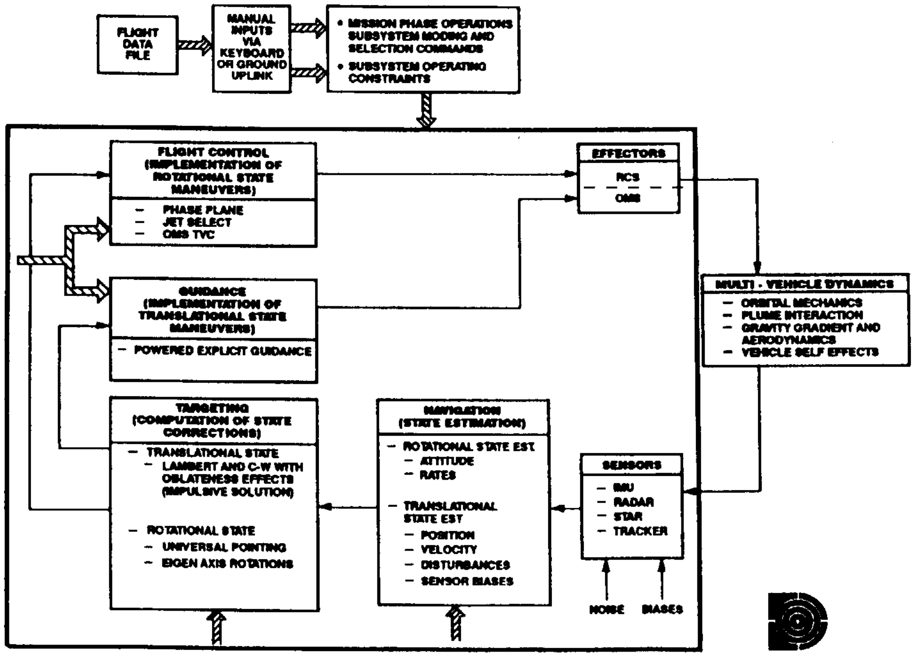
- Assess the capabilities (and limitations) of the current AR&D system configuration to satisfy the following top level system requirements:
  - Rendezvous Mission Phase
    - — Bring the active vehicle to the start of the proximity operations phase within a specified 3σ dispersion ellipse relative to the target and consistent with the mission design.
    - — Satisfy the trajectory and the consumables constraints of both vehicles
    - — Achieve the above objective for:
      - Dispersed conditions at the start of the rendezvous
      - Sensor and effector failures and subsequent system reconfigurations
  - Proximity Operations Mission Phase
    - — Maintain the relative position, velocity, and attitude between the chaser and the target vehicle within defined limits along a a desired approach profile consistent with mission design
    - — Achieve docking conditions consistent with docking mechanism capabilities
    - — Satisfy the above objectives for:
      - Dispersed conditions at the start of the rendezvous
      - Sensor and effector failures and subsequent system reconfigurations
    - — Considered as operations within 1 nm of the target
- To the extent possible, standardization of system design, trajectory profiles,operations, procedures, and sensor requirements across various programs
- Identify IGN&C interaction problems and intervehicular problems
- Sensor, effectors and algorithm trade studies

PERFORMANCE ANALYSIS OVERVIEW (cont'd)

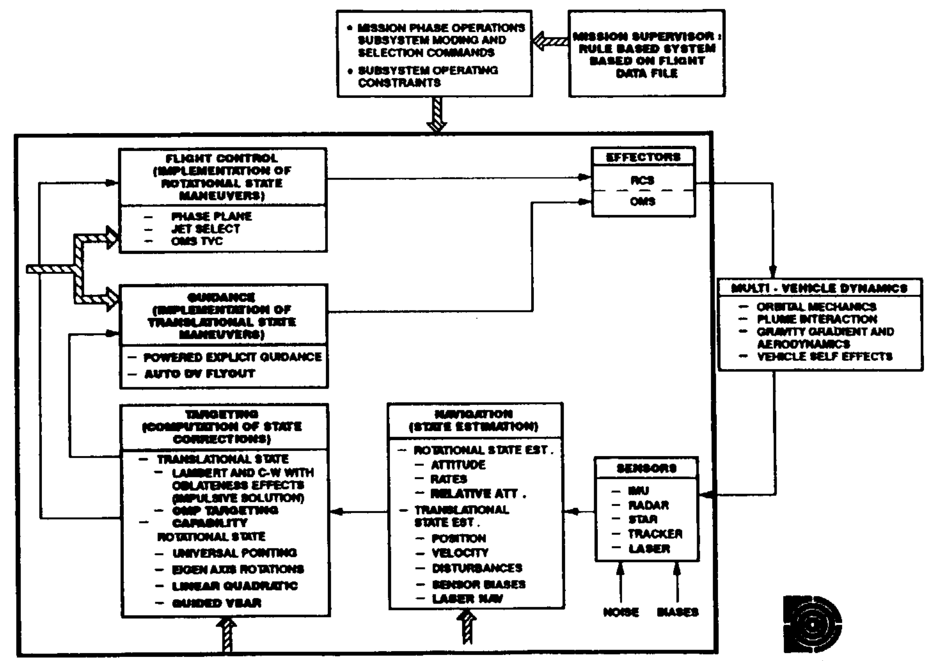
DISCUSSION

- The top level system requirements can be achieved with different levels of "success" depending on the capabilities of a given AR&D system configuration.
- The analysis approach consistent with the "Phased" development of AR&D system capabilities is as follows:
  - — Evaluate the performance capabilities and limitations of a Shuttle type AR&D system with:
    - Minimum set of software upgrades to provide an initial AR&D capability
    - Addition of a sensor to provide the necessary relative navigation capability
  - — Modify the AR&D system design as dictated by analysis results and evaluate the performance improvements.
    - Modifications to the basic system design (algorithms, rates, etc.)
    - Adding increasingly complex technology capabilities
    - Improved sensor / actuator complements
- This process defines a set of AR&D systems and their attendant capabilities which satisfy an increasingly complex set of AR&D requirements.

SHUTTLE IGN&C SYSTEM SCHEMATIC



AR&D CANDIDATE SYSTEM DEVELOPED FROM SHUTTLE IGN&C SYSTEM REQUIREMENTS



IGN&C PERFORMANCE ANALYSIS DATA BASE

IGN&C SOFTWARE IMPLEMENTATION

- Baseline shuttle software requirements with the following upgrades:
  - "Trajectory control" / profile guidance algorithms
    - Rendezvous: generalized rendezvous maneuver sequencer
    - Proximity operations
      - "Guided VBAR"
      - Linear quadratic stationkeeping with linear, "CW", and "Optimal VBAR" trajectory seqments
      - "Optimal VBAR"
      - Glide slope Controller
      - Cusp profile
  - Navigation
    - Absolute (inertial) and relative GPS with different measurement type incorporation algorithms and relative state determination techniques.
    - Relative attitude determination using laser measurements: Kalman filter and deterministic
    - Laser relative nav: Kalman filter and deterministic
- Control
  - Auto selection of RCS jets and DAP moding

IGN&C PERFORMANCE ANALYSIS DATA BASE (cont'd)

- IGN&C
  - Rudimentary "automatic" sequencer operation
  - Executive structure modifications to provide properly phased software execution (minimize transport lags and provide improved performance)
  - Auto maneuver logic for executing commanded "trajectory control" maneuvers in preferred axis sequence. Uses modeled jet thrust for maneuver execution in order to achieve minimum impulse maneuver levels.
  - Automatic pilot models, as required
- Sensors
  - Radar (Shuttle Sensor Specification)
  - Optical (Shuttle Sensor Specification)
  - Global Positioning System
  - Laser proximity operations sensor (Comm. & Track Sensor Specification)
  - VHF ranging
  - IMU (Shuttle Sensor Specification)
- Standardization of targeting/guidance, navigation and control interfaces
  - Facilitates development/assessment of phased upgrades to the AR&D system

IGN&C SYSTEM DEVELOPMENT AND ANALYSIS SIMULATIONS

GUIDANCE AND NAVIGATION

- On-orbit, rendezvous and prox ops mission phases
  - — 3 DOF closed loop engineering simulation capabilities
    - Monte Carlo analysis
    - Linearized covariance analysis
    - Trajectory dispersion analysis
- Ascent mission phase: capability to generate initial conditions for on orbit phases
  - — 3 DOF closed loop engineering simulation capabilities
    - Monte Carlo
  - — 3 DOF open loop nav specific simulation capabilities
    - Monte Carlo analysis
    - Linearized covariance analysis

FLIGHT CONTROL

- Space Systems simulation
  - — 6 DOF models for two active spacecraft
  - — Ideal navigation and guidance
  - — Flight control and effector models for different spacecraft
    - Shuttle, Space Station, OMV
- Control effectors modeled
  - — RCS, CMG's, reaction wheels, magnetic torquers
- Environment models based on OFS
- "Crew station" to assess MIL interface/interaction
  - — RHC, THC
  - — Displays, spec functions, keyboard

IGN&C SYSTEM DEVELOPMENT AND ANALYSIS SIMULATIONS (cont'd)

IGN&C

- Multi 6 DOF Vehicle On-Orbit Functional Simulation (MVOFS)
  - — Monte Carlo and discrete run capability
  - — High fidelity environment, vehicle and sensor models
  - — Includes plume impingement effects on the vehicles
  - — Complete IGN&C system software capability for all vehicles
    - Shuttle IGN&C system architecture and software requirements with enhanced capabilities as discussed above

- MVOFS is derived from OFS which has been used extensively for:
  - — Shuttle IGN&C rendezvous system design and performance evaluation
  - — Shuttle flight software verification signature data
  - — SES rendezvous capability signature run
  - — Advanced capabilities development

RENDEZVOUS MISSION PHASE PERFORMANCE ANALYSIS FOR CANDIDATE AR&D SYSTEM DESIGN

CSDL

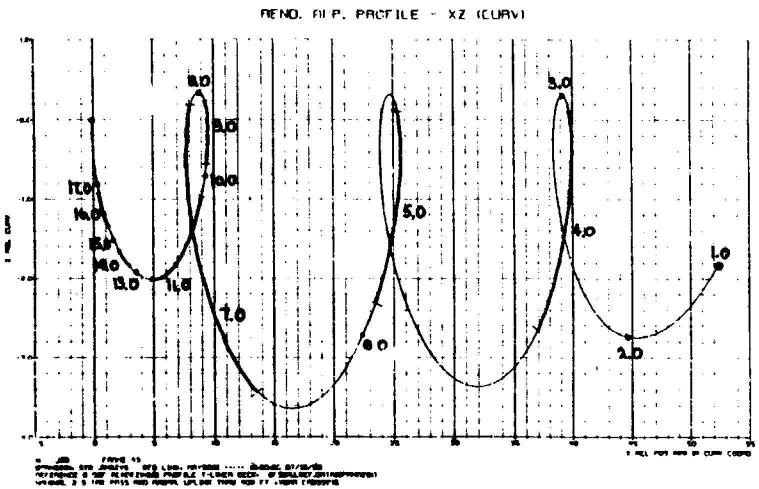
RENDEZVOUS PERFORMANCE FIGURES OF MERIT

- System level
  - — Resultant 3σ trajectory dispersions at start of prox ops phase
  - — Mission design capabilities
- Subsystem level
  - — Maneuver targeting errors
  - — System performance capability with degraded and failed sensors
  - — Sensitivity to maneuver execution errors and effector failures
  - — Dispersion handling capabilities at start of rendezvous phase
  - — Fuel usage
  - — Relative profile integrity
    - Dispersions at critical maneuver points
    - "Integrity" of relative profile
  - — Sensor aquisition search volume
  - — Failure identification, reconfiguration and recovery
  - — Applicability of subsystem design to a "genuine" AR&D system
  - — Normal, contingency and stress case performance
  - — Finite target effects as close ranges to the target

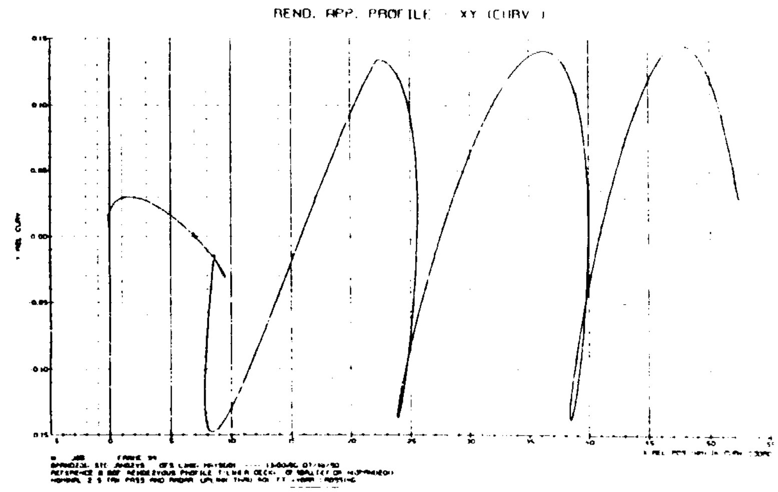
PERFORMANCE ANALYSIS RESULTS

- Earth Operations
  - — Mission profiles
    - Shuttle operational mission design
    - Autonomous rendezvous profile for Shuttle approach to the the station which provides:
      - — Consistent entry conditions to the command and control zone (CCZ)
      - — Consistent keel crossing distance from the target
    - This profile shows on-board performance capabilities of the system at long ranges
  - — Brief summary of results follows

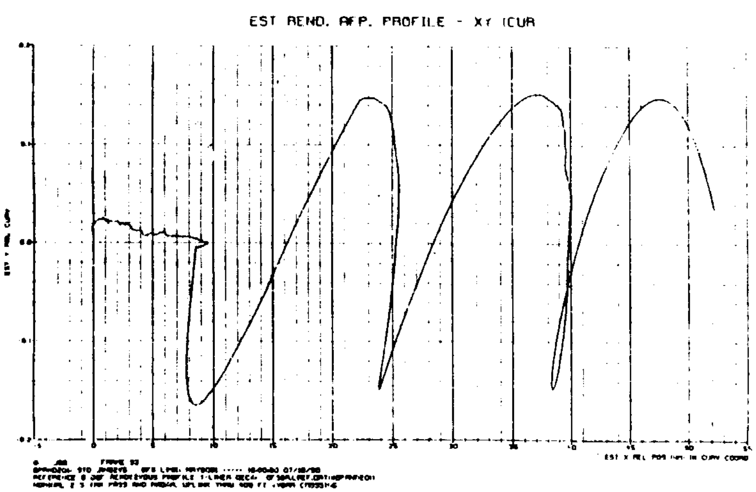
LDEF RENDEZVOUS PROFILE



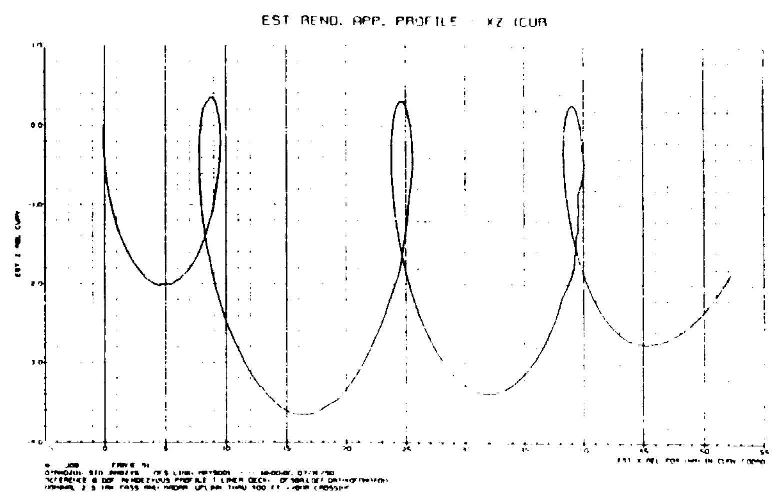
LDEF RENDEZVOUS PROFILE (cont'd)



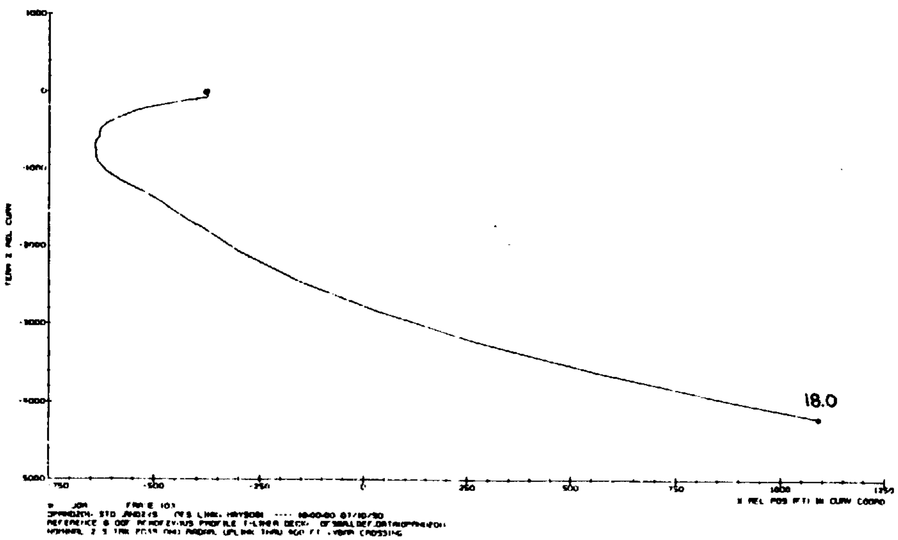
LDEF RENDEZVOUS PROFILE (cont'd)



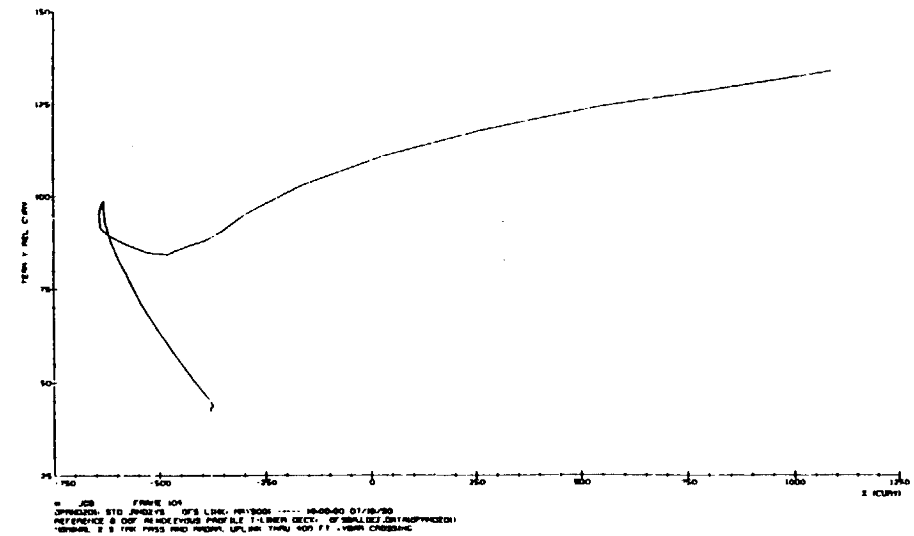
LDEF RENDEZVOUS PROFILE (cont'd)



LDEF TERMINAL PHASE PROFILE
MCC4 TO VBAR STATIONKEEPING



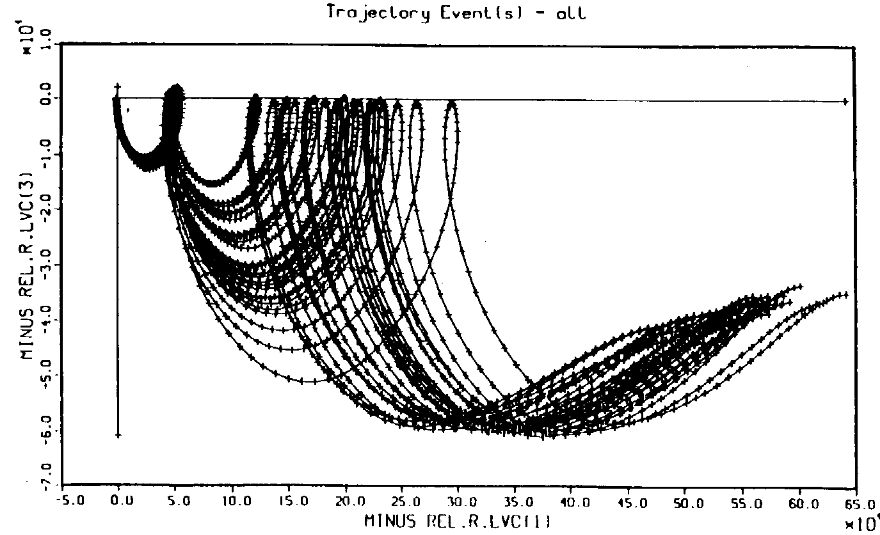
LDEF TERMINAL PHASE PROFILE (cont'd)
MCC4 TO VBAR STATIONKEEPING



LDEF RETRIEVE MISSION TIMELINE

TIME	EVENT		EVENT DESCRIPTION
0.0	Ground uplink	1.0	Ground uplink of Shuttle and Target states with a height and phasing maneuver pair
29.3	NH burn	2.0	Execution of ground targeted height maneuver
74.9	NC burn	3.0	Execution of ground target phasing maneuver
82.6 — 103.9	ST rel nav	4.0	Star tracker relative navigation with reflected sunlight from the target
173.1 — 196.1	ST rel nav	5.0	Star tracker relative navigation with reflected sunlight from the target
198.15	NCC burn	6.0	Execute onboard Lambert targeted correction burn to hit offset point
220.6 — 256.4	RR nav	7.0	Rendezvous radar relative tracking
257.3	TI burn	8.0	Execute onboard targeted burn to intercept the target
259.2 — 281.2	RR nav	9.0	Rendezvous radar nav (and star tracker if required)
283.4	MC1	10.0	Midcourse Correction 1
284.9 — 310.9	RR nav	11.0	RR nav. Target goes into darkness about 8 minutes after MC1 precluding use of star tracker after this time
288.2	Out-of-plane null maneuver	12.0	Out-of-plane null maneuver executed at estimated planar crossing. Orbiter is in target orbit plane following the maneuver
312.6	MC2	13.0	Midcourse correction 2
314.1 — 320.6	RR nav	14.0	RR relative nav
322.6	MC3	15.0	Midcourse correction 3
324.1 — 330.6	RR nav	16.0	RR relative nav
332.5	MC4	17.0	Midcourse correction 4
332.5+	Manual phase	18.0	Manual proximity operations phase initiation

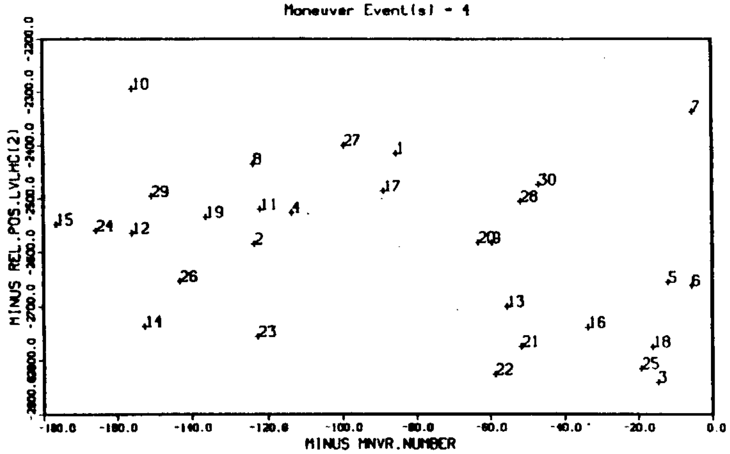
MONTE CARLO STUDY FOR FINITE SPACE STATION EFFECTS RENDEZVOUS STUDY



MONTE CARLO STUDY FOR FINITE SPACE STATION EFFECTS RENDEZVOUS STUDY (cont'd)

S1FRONA6 KEEL CROSSING

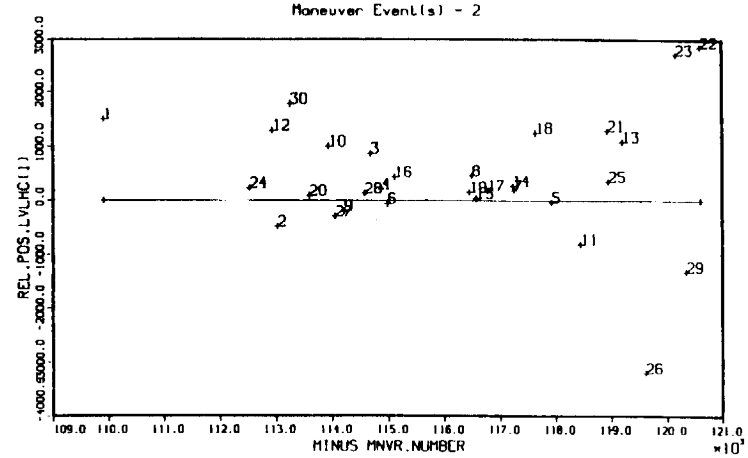
File - 6
Run(s) - 1 to 30
Maneuver Event(s) - 4



MONTE CARLO STUDY FOR FINITE SPACE STATION EFFECTS RENDEZVOUS STUDY (cont'd)

S1FRONA6 CCZ ENTRY CONDITIONS

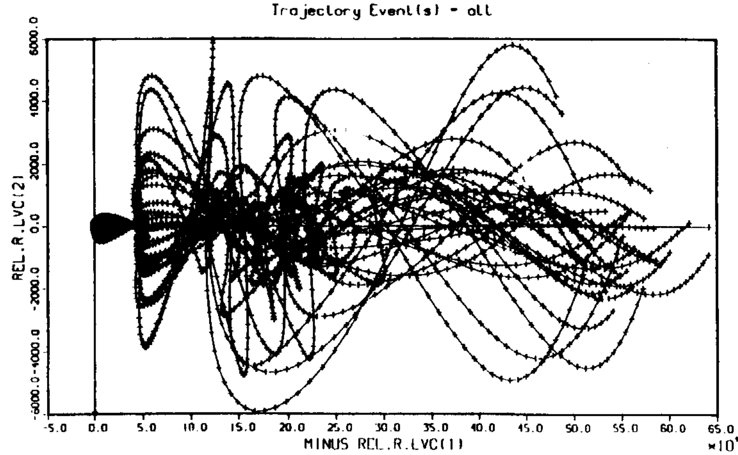
File - 6
Run(s) - 1 to 30
Maneuver Event(s) - 2



MONTE CARLO STUDY FOR FINITE SPACE STATION EFFECTS RENDEZVOUS STUDY (cont'd)

EH60NB01

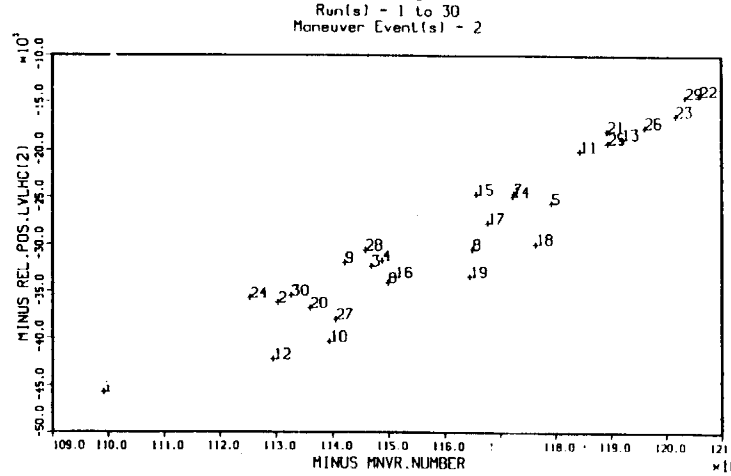
File - 7
Run(s) - 1 to 30
Trajectory Event(s) - all



MONTE CARLO STUDY FOR FINITE SPACE STATION EFFECTS RENDEZVOUS STUDY (cont'd)

S1FRONA6 CCZ ENTRY CONDITIONS

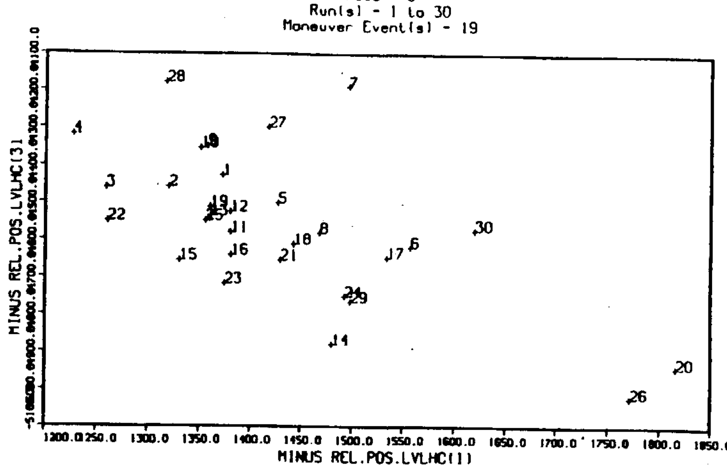
File - 6
Run(s) - 1 to 30
Maneuver Event(s) - 2



MONTE CARLO STUDY FOR FINITE SPACE STATION EFFECTS RENDEZVOUS STUDY (cont'd)

S1FRONA6 MC4

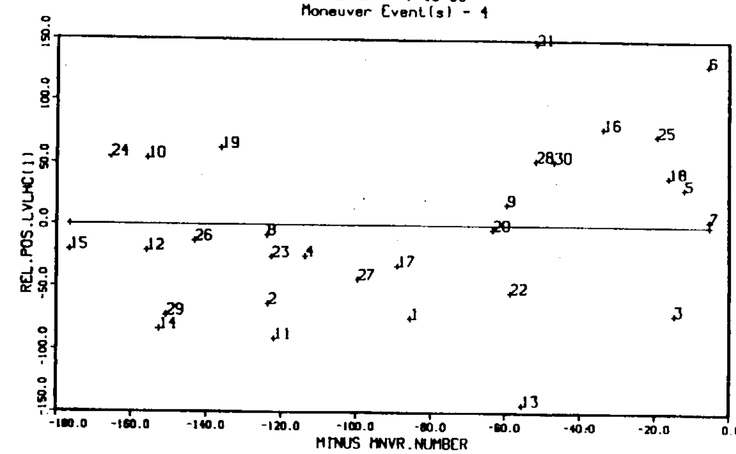
File - 6
Run(s) - 1 to 30
Maneuver Event(s) - 19



MONTE CARLO STUDY FOR FINITE SPACE STATION EFFECTS RENDEZVOUS STUDY (cont'd)

S1FRONA6 KEEL CROSSING

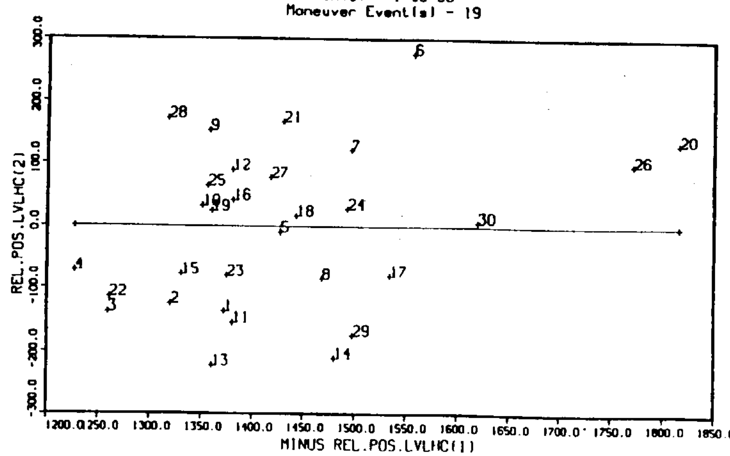
File - 6
Run(s) - 1 to 30
Maneuver Event(s) - 4



MONTE CARLO STUDY FOR FINITE SPACE STATION EFFECTS RENDEZVOUS STUDY (cont'd)

S1FRONA6 MC4

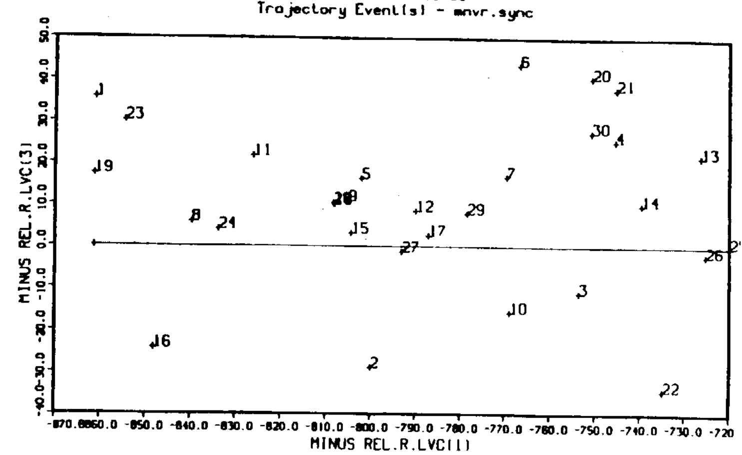
File - 6
Run(s) - 1 to 30
Maneuver Event(s) - 19



MONTE CARLO STUDY FOR FINITE SPACE STATION EFFECTS RENDEZVOUS STUDY (cont'd)

S1FRONA6

File - 7
Run(s) - 1 to 30
Trajectory Event(s) - mnvr.sync



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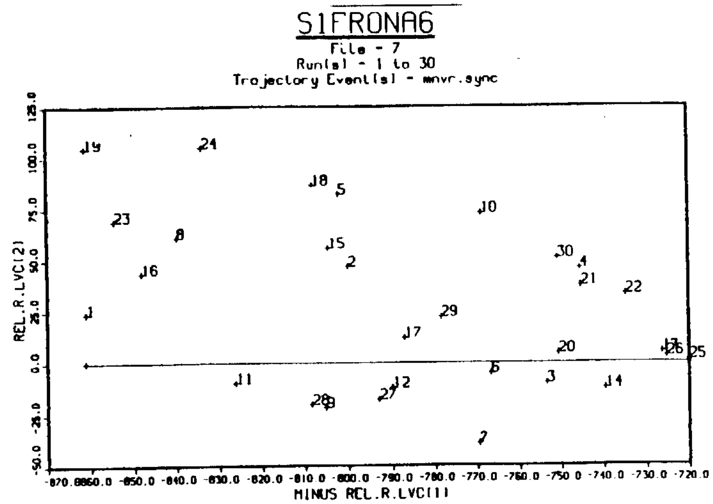
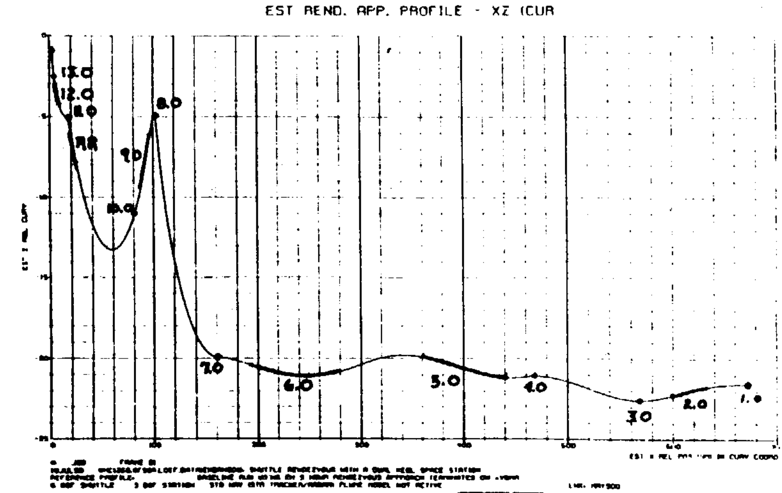
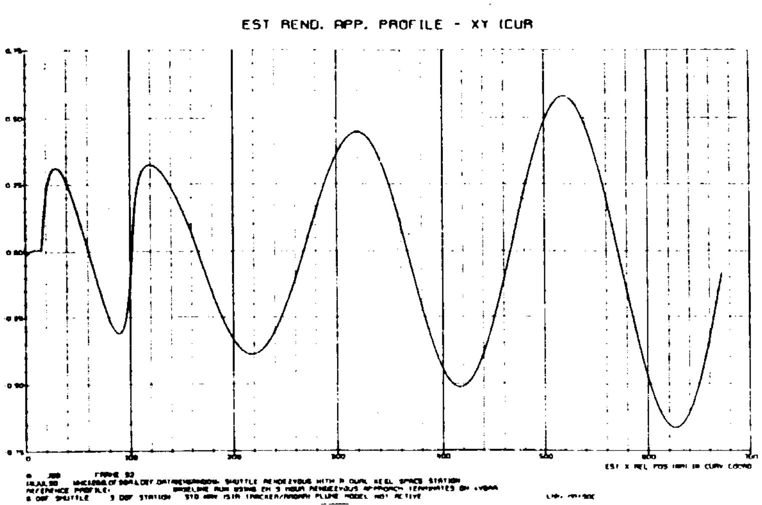
MONTE CARLO STUDY FOR FINITE SPACE STATION EFFECTS RENDEZVOUS STUDY (cont'd)



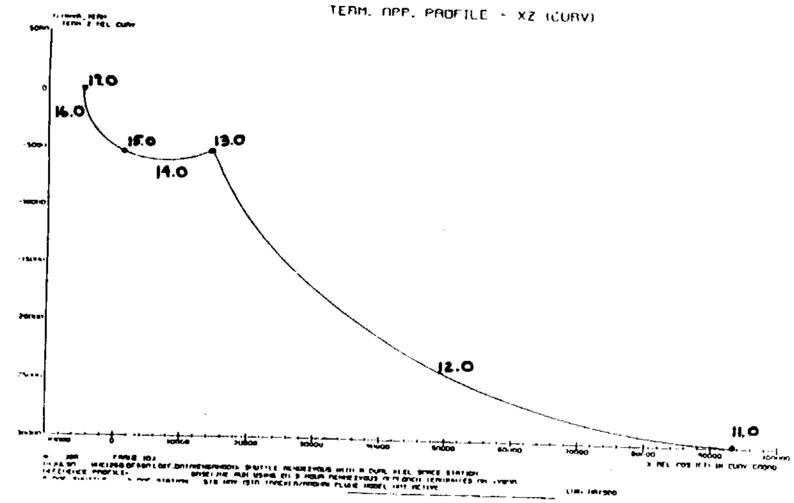
A LONG RANGE RENDEZVOUS PROFILE FOR SPACE STATION OPERATIONS



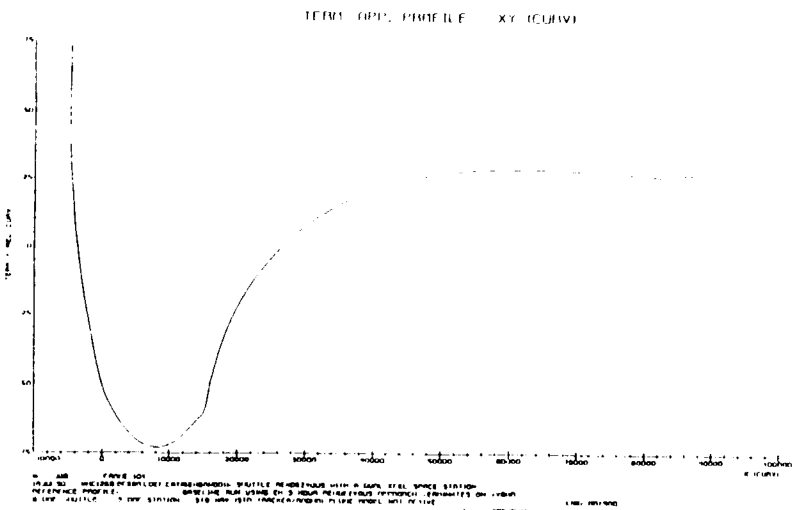
A LONG RANGE RENDEZVOUS PROFILE FOR SPACE STATION OPERATIONS (cont'd)



A LONG RANGE RENDEZVOUS PROFILE FOR SPACE STATION OPERATIONS (cont'd)



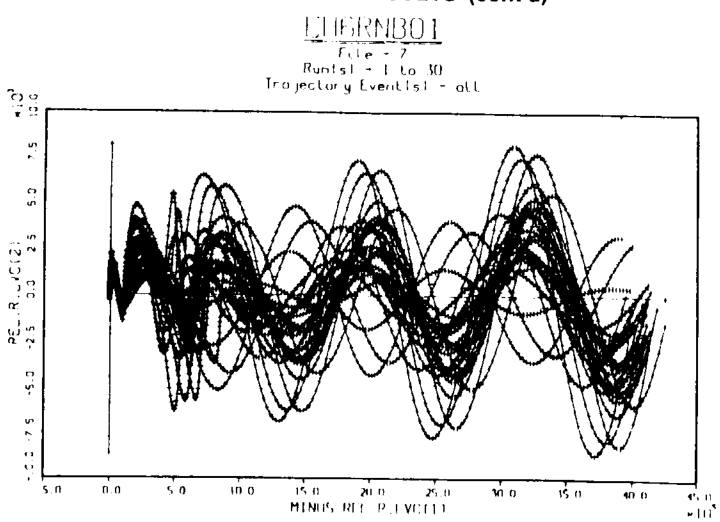
A LONG RANGE RENDEZVOUS PROFILE FOR SPACE STATION OPERATIONS (cont'd)



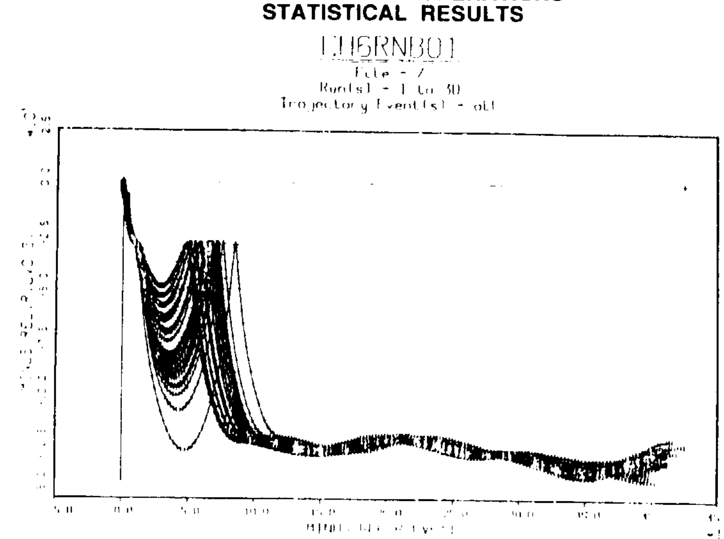
LONG RANGE RENDEZVOUS TIMELINE

TIME	EVENT		EVENT DESCRIPTION
0.0	Ground uplink	1.0	Ground uplink of orbiter and target vehicle states
3.1 — 29.3	ST rel nav	2.0	Star tracker relative nav if target is visible in reflected sunlight
45.0	NHO	3.0	Height adjust maneuver to control coelliptic altitude to mission design value
93.0	NSR	4.0	Coelliptic maneuver
97.3 — 123.7	ST rel nav	5.0	Star tracker relative nav with target in reflected sunlight
188.7 — 218.3	ST rel nav	6.0	Star tracker relative nav with target in reflected sunlight
242.8	NH1	7.0	Height adjust maneuver targeted in combined with the following phase adjust maneuver. Targeting for mission designed relative phasing and altitude at CCZ entry
289.9	NC1	8.0	Phasing maneuver to control phasing at CCZ entry
294.6 — 312.8	ST rel nav	9.0	ST rel nav with target in reflected sunlight
320.8	NCC	10.0	Lambert targeted corrective maneuver to insure desired CCZ entry
383.6	NC01	11.0	Lambert targeted maneuver to control height and phasing at start of keel crossing phase. ~180 deg transfer angle so no out of plane correction is made
396.6 — 420.4	RR rel nav	12.0	Rendezvous radar relative nav skin track of the target
430.4	NCC1	13.0	Lambert targeted corrective maneuver
433.0 — 446.7	RR rel nav	14.0	Rendezvous radar relative nav
448.7	MC1	15.0	Midcourse Lambert targeted to control desired VBAR crossing
450.24 — 466.75	RR rel nav	16.0	Rendezvous radar relative nav
468.7	NCC2	17.0	Execute NCC2 maneuver: — Either a relative velocity null to stationkeeping on VBAR or Lambert targeted "midcourse" correction to the desired guided VBAR approach initiation point — Proximity operations phase initiated

LONG RANGE AUTONOMOUS RENDEZVOUS FOR SPACE STATION OPERATIONS STATISTICAL RESULTS (cont'd)



LONG RANGE AUTONOMOUS RENDEZVOUS FOR SPACE STATION OPERATIONS STATISTICAL RESULTS



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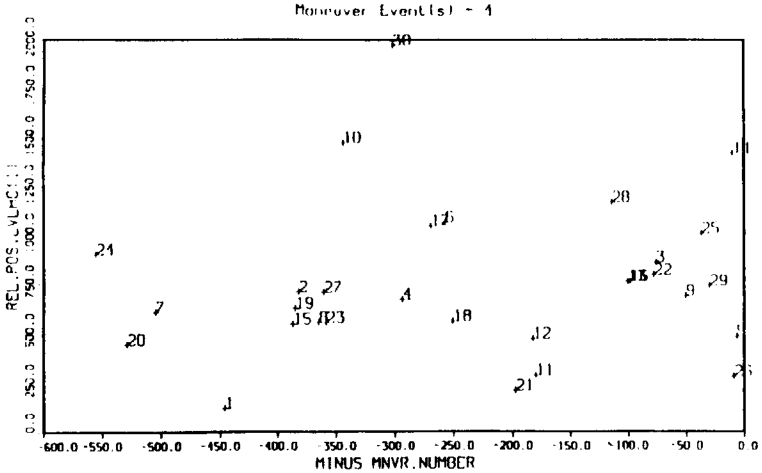
LONG RANGE AUTONOMOUS RENDEZVOUS FOR SPACE STATION OPERATIONS STATISTICAL RESULTS (cont'd)

LHR6DNB KEEL CROSSING

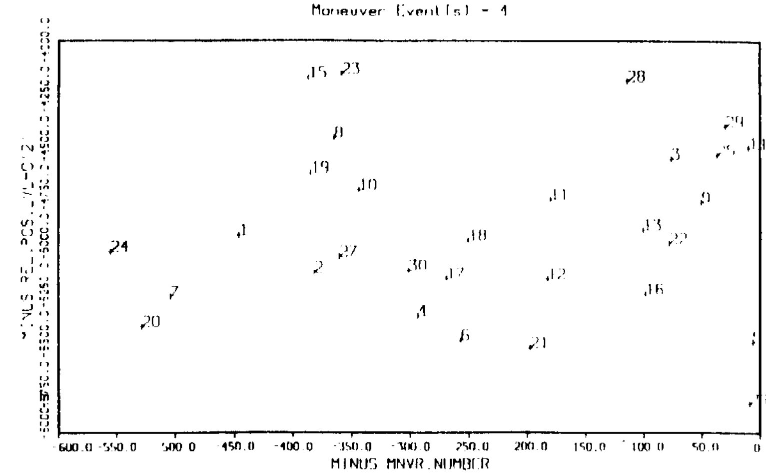
File - 6
Run(s) - 1 to 30
Maneuver Event(s) - 4



LONG RANGE AUTONOMOUS RENDEZVOUS FOR SPACE STATION OPERATIONS STATISTICAL RESULTS (cont'd)

LHR6DNB KEEL CROSSING

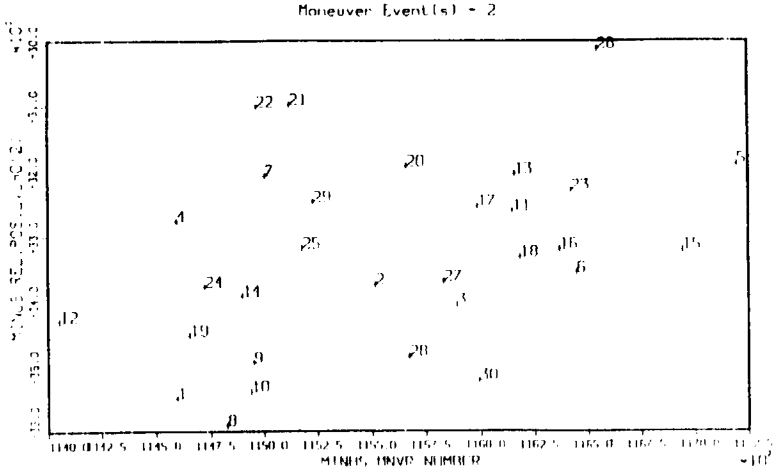
File - 6
Run(s) - 1 to 30
Maneuver Event(s) - 4



LONG RANGE AUTONOMOUS RENDEZVOUS FOR SPACE STATION OPERATIONS STATISTICAL RESULTS (cont'd)

LHR6DNB CCZ ENTRY CONDITIONS

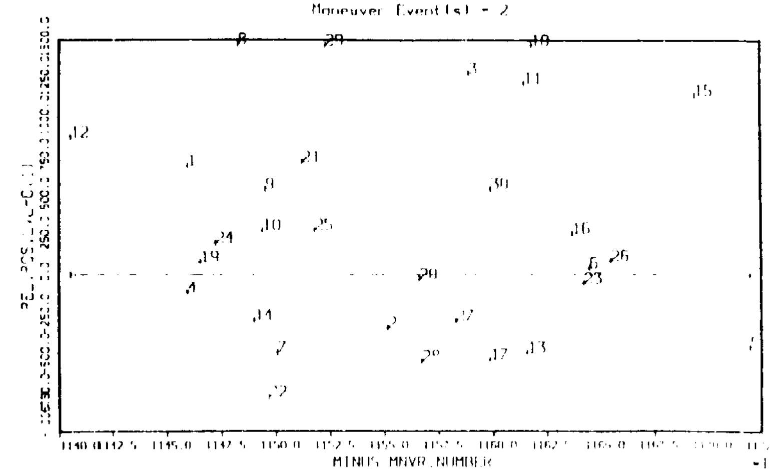
File - 6
Run(s) - 1 to 30
Maneuver Event(s) - 2



LONG RANGE AUTONOMOUS RENDEZVOUS FOR SPACE STATION OPERATIONS STATISTICAL RESULTS (cont'd)

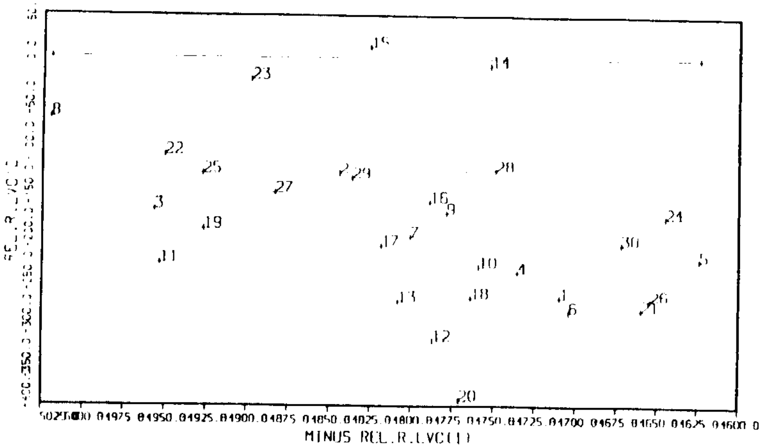
LHR6DNB CCZ ENTRY CONDITIONS

File - 6
Run(s) - 1 to 30
Maneuver Event(s) - 2



LONG RANGE AUTONOMOUS RENDEZVOUS FOR SPACE STATION OPERATIONS STATISTICAL RESULTS (cont'd)

CH6RNB01
File - 7
Run(s) - 1 to 30
Trajectory Event(s) - mnvr.sync



SPACE STATION RENDEZVOUS PROFILE ENGINEERING EVALUATION STATISTICAL RESULTS

OPERATIONAL PROFILE

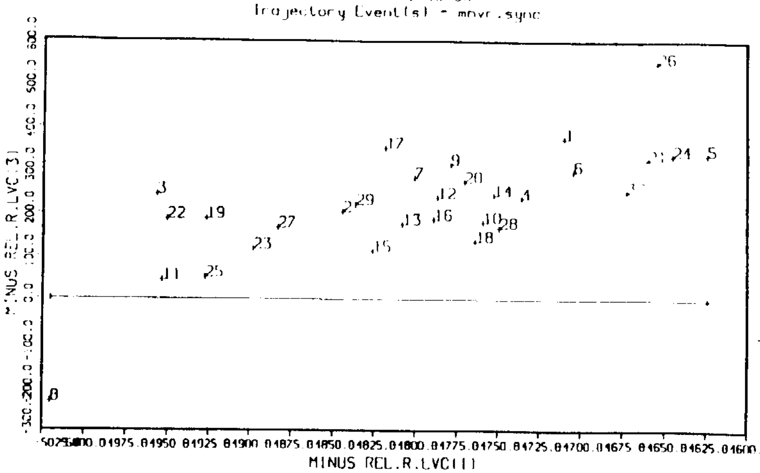
RUN DESIG	D O F NO OF SAMPLES OR M C SET NO	SRCE OF FSE ERR AND ENV DISP	NAV SENSOR TRACK: G.U. TO NH2	NH2 TO NC3	NC3 TO NCC	NCC TO T I	T I TO MCC1	MCC1 TO MCC2	MCC2 TO MCC3	MCC3 TO MCC4	POST MCC4	RELATIVE POSITION SUMMARY IN N M (LV CURV FRAME) MEAN 1 SIGMA: GROUND UPLINK		NH2 (GROUND TARGETED)		NC3 (GROUND TARGETED)	
EHO6NB00	6 DOF 30 MC	MPAD	ST	-	ST	RR	RR	RR	RR	RR	RR	0 0	91 2, 02, 6 3	45 0	55 7, 0, 9 8	93 2	71 2, 0, 2
EHO6NB01	6 DOF 30 MC	MPAD	ST	-	ST	RR	RR	RR	RR	RR	RR	0 0	91 2 04, 6 1 6 5, 2, 4	45 0	55 8 04 9 7 7 3, 20, 1	92 2	31 4 01, 20 6 9, 20, 1

REFERENCE PROFILE

RUN DESIG	D O F NO OF SAMPLES OR M C SET NO	SRCE OF FSE ERR AND ENV DISP	NAV SENSOR TRACK: G U TO NHO	NHO TO NSR	NSR TO NH1		NH1 TO NC1	NC1 TO NCC	NCC TO NH2	NH2 TO MCC1	MCC1 TO MCC1	MCC1 TO MCC2	RELATIVE POSITION SUMMARY IN N M (LV CURV FRAME) MEAN 1 SIGMA: GROUND UPLINK		NHO		NSR	
EHR6NB00	6 DOF 30 MC1	MPAD	ST	-	ST	ST	RR	RR	RR	RR	RR	RR	0 0	671 06 21 6		574, 05, 22 6	91 9	466 7 0 20 9
EHR6NR01	6 DOF 30 MC1	MPAD	ST	-	ST	ST	RR	RR	RR	RR	RR	RR	0 0	671 08 21 6 11, 22, 8	45 0 0	574 01, 22 4 14 20, 3	91 9 0 0	461, 02 21 11 2, 1

LONG RANGE AUTONOMOUS RENDEZVOUS FOR SPACE STATION OPERATIONS STATISTICAL RESULTS (cont'd)

CH6RNB01
File - 7
Run(s) - 1 to 30
Trajectory Event(s) - mnvr.sync



SPACE STATION RENDEZVOUS PROFILE ENGINEERING EVALUATION STATISTICAL RESULTS (cont'd)

OPERATIONAL PROFILE

RUN DESIG	D O F NO OF SAMPLES OR M C SET NO	SRCE OF FSE ERR AND ENV DISP	NAV SENSOR TRACK: G U TO NH2	NH2 TO NC3	NC3 TO NCC	NCC TO T I	T I TO MCC1	MCC1 TO MCC2	MCC2 TO MCC3	MCC3 TO MCC4	POST MCC4	RELATIVE POSITION SUMMARY IN N M (LV CURV FRAME) MEAN 1 SIGMA: NCC		T I		MCC1	
EHO6NB00	6 DOF 30 MC	MPAD	ST	-	ST	RR	RR	RR	RR	RR	RR	128 6	26 6, 0, 3 8	187 7	8 6, 03, 7	213 8	8 9, 0, 96
EHO6NB01	6 DOF 30 MC	MPAD	ST	-	ST	RR	RR	RR	RR	RR	RR	128 6	26 9 01 3 7 5 5, 24 1 3	187 7	8 9 02 25 2 1 0	213 8	8 1 0 92 3, 02, 1

REFERENCE PROFILE

RUN DESIG	D O F NO OF SAMPLES OR M C SET NO	SRCE OF FSE ERR AND ENV DISP	NAV SENSOR TRACK: G U TO NHO	NHO TO NSR	NSR TO NH1		NH1 TO NC1	NC1 TO NCC	NCC TO NH2	NH2 TO MCC1	MCC1 TO MCC1	MCC1 TO MCC2	RELATIVE POSITION SUMMARY IN N M (LV CURV FRAME) MEAN 1 SIGMA: NH1		NC1		NCC	
EHR6NB00	6 DOF 30 MC1	MPAD	ST	-	ST	ST	RR	RR	RR	RR	RR	RR	242 8	159 2 08, 19 9	289 9	101 6 04 4 88	320 8	80 5, 0, 28
EHR6NR01	6 DOF 30 MC1	MPAD	ST	-	ST	ST	RR	RR	RR	RR	RR	RR	242 8 0	160 09 20 0 14, 34, 10	289 9 0 0	102 05, 4 8 14 05 05	320 8 0	81 3, 2 11 12 2 2 1

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SPACE STATION RENDEZVOUS PROFILE
ENGINEERING EVALUATION
STATISTICAL RESULTS (cont'd)

OPERATIONAL PROFILE

RUN DESIG	D.O.F. NO. OF SAMPLES OR M.C. SET NO	SRCE OF ESE ERR AND ENV DISP.	NAV SENSOR TRACK G.U TO NH2	NH2 TO NC3	NC3 TO NCC	NCC TO T.I	T.I TO MCC1	MCC1 TO MCC2	MCC2 TO MCC3	MCC3 TO MCC4	POST MCC4	RELATIVE POSITION SUMMARY IN FT (LV CURV FRAME) MEAN 1 SIGMA: MCC2		MCC3		MCC4	
EHO6NBOO	6 DOF 30 MC	MPAD	ST	-	ST	RR	RR	RR	RR	RR	RR	240 2 1 4	-3 7, .07, 2 0		9560, 163, 9269		-1714, 126, 5036
EHO6NBO1	6 DOF 30 MC	MPAD	ST	-	ST	RR	RR	RR	RR	RR	RR	239 8 6	-3 3, 0, 1 8 .2, .02, 1		-8631, -34, 8501 408, 160, 378		-1461, -62, 4595 95, 131, 213

REFERENCE PROFILE

RUN DESIG	D.O.F. NO. OF SAMPLES OR M.C. SET NO.	SRCE OF FSE ERR AND ENV DISP.	NAV SENSOR TRACK G.U. TO NHO	NHO TO NSR	NSR TO NH1		NH1 TO NC1	NC1 TO NCC	NCC TO NH2	NH2 TO MCC1	MCC1 TO MCC1	MCC1 TO MCC2	RELATIVE POSITION SUMMARY IN N M (LV CURV FRAME) MEAN 1 SIGMA: NH2		MCC1		MCC1	
EHRGNBOO	6 DOF 30 MC1	MPAD	ST	-	ST	ST	RR	RR	RR	RR	RR	RR	383 4	-16.0, 0, 4 9	430 4	-2 5, .0, 82	448 7	-1905, 102, 5191
EHRGNBO1	6 DOF 30 MC1	MPAD	ST	-	ST	ST	RR	RR	RR	RR	RR	RR	383 4 0	-16 3, -.14, 4 9 61, .03, 04	430 4	-2 7, 13, 84 60, .03, 04	448 7	-1732, 840, 5627 1857, 403, 1069

SPACE STATION RENDEZVOUS PROFILE
ENGINEERING EVALUATION
STATISTICAL RESULTS (cont'd)

OPERATIONAL PROFILE

RUN DESIG	D.O.F. NO. OF SAMPLES OR M.C. SET NO	SRCE OF FSE ERR AND ENV DISP	NAV SENSOR TRACK G.U TO NH2	NH2 TO NC3	NC3 TO NCC	NCC TO T.I	T.I TO MCC1	MCC1 TO MCC2	MCC2 TO MCC3	MCC3 TO MCC4	POST MCC4	FUEL USAGE TO VBAR STATIONKEEPING MEAN 1 SIGMA: LEFT OMS	RT OMS	TOT OMS	RCS FWD AT	RCS FWD TRDN	RCS FWD TOT	RCS AFT ATT	RCS AFT TRDN	RCS AFT TOT	TOT RCS F&A
EHO6NBOO	6 DOF 30 MC	MPAD	ST	-	ST	RR	RR	RR	RR	RR	RR	369 369	0 0 0 0	369 369	76 84	120 164	196 248	121 139	279 398	400 537	596 785
EHO6NBO1	6 DOF 30 MC 30 MC 30 MC	MPAD	ST	-	ST	RR	RR	RR	RR	RR	RR	466 71 466 71	13 38 13 38	479 73 479 73	83 9 102 11	76 41 138 40	160 37 241 37	136 18 175 22	218 100 357 98	357 89 532 89	517 122 773 122

REFERENCE PROFILE

RUN DESIG	D.O.F. NO. OF SAMPLES OR M.C. SET NO	SRCE OF FSE ERR AND ENV DISP.	NAV SENSOR TRACK G.U TO NHO	NHO TO NSR	NSR TO NH1		NH1 TO NC1	NC1 TO NCC	NCC TO NH2	NH2 TO MCC1	MCC1 TO MCC1	MCC1 TO MCC2	FUEL USAGE TO VBAR CROSSING POST/MCC2 MEAN 1 SIGMA: LEFT OMS	RT OMS	TOT OMS	RCS FWD AT	RCS FWD TRDN	RCS FWD TOT	RCS AFT ATT	RCS AFT TRDN	RCS AFT TOT	TOT RCS F&A
EHRGNBOO	6 DOF 30 MC1	MPAD	ST	-	ST	ST	RR	RR	RR	RR	RR	RR	886	473	1359	124	243	366	232	287	519	886
EHRGNBO1	6 DOF 30 MC1	MPAD	ST	-	ST	ST	RR	RR	RR	RR	RR	RR	861 84	546 55	1408 89	129 11	250 62	379 61	217 19	325 60	542 60	921 106

SUMMARY OF RESULTS

- Both profiles achieve their respective prox ops initiation point with a small dispersion ellipse
  - MCC4 for operational profile
  - VBAR crossing for long range profile
- Performance results for both profiles, with nav sensors degraded to 3 sigma spec value, are essentially the same as shown since filter variance loads are already downweighted to for nominal operation
- Long range rendezvous profile provides for a consistent Station Command and Control Zone entry location and keel crossing
- Current AR&D system configuration provides good rendezvous system performance

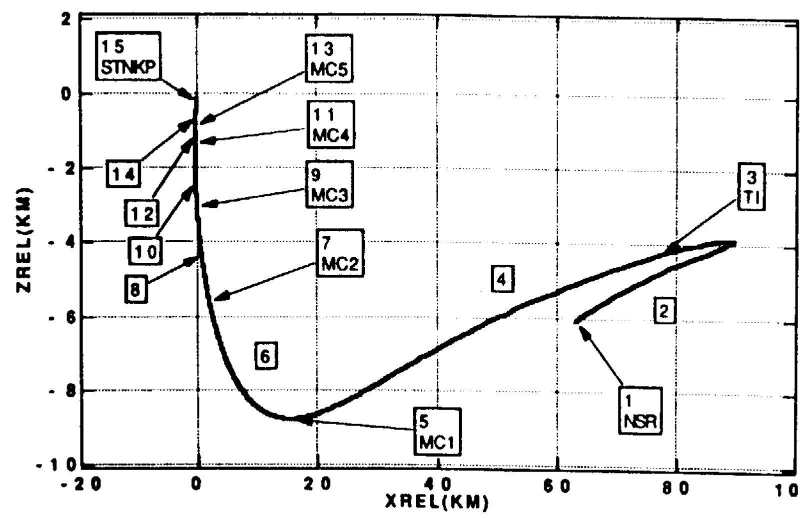
MARS RENDEZVOUS PERFORMANCE

- Four profiles currently under investigation
  - "Reference" coelliptic profile
  - Highly elliptic profile (1 SOL x 500 km)
  - "Stable orbit" profile
  - Extended duration Deep Space Network Supported Rendezvous
- Initial feasablity studies have shown that Shuttle quality sensors, with the appropriate rendezvous profile design, can achieve acceptable dispersions at the start of the Proximity Operations Phase
- Detailed results have been presented at JSC
- A summary of results and rendezvous profile overview for the highly elliptic study is shown

HIGHLY ELLIPTIC (1 SOL) RENDEZVOUS

- Two rendezvous scenarios are initially being analyzed
  - — Rendezvous at apoapse
  - — Rendezvous at periapse
- Trajectory initial conditions were obtained from elliptical relative profile study presented at JSC on March 28, 1990
- Onboard relative nav was initiated one hour prior to the desired intercept initiation maneuver time (T.I.)
- DSN quality, uplink nav error covariance values were assumed for both the target and chaser vehicles at the start of on board relative navigation
- For this study it was assumed that the vehicles were placed in the correct relative phasing within the DSN quality uplink error capability

MARS APOAPSE RENDEZVOUS RELATIVE TRAJECTORY

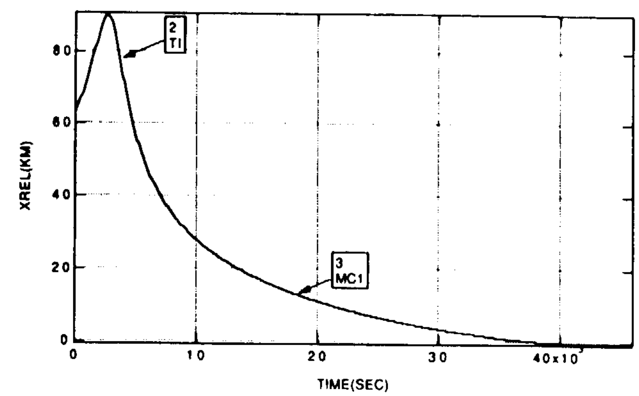


APOAPSE RENDEZVOUS

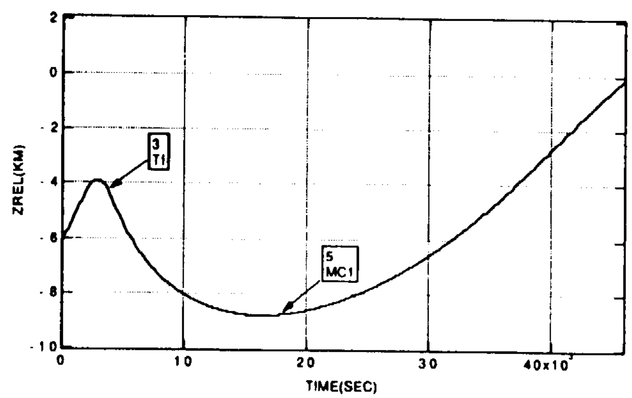
TIMELINE

TIME	EVENT		EVENT DESCRIPTIONS
0.0	NSR	1.	Initiate rendezvous phase at coelliptic condition relative to the target
		2.	Relative nav
60.0	T.I.	3.	Transfer initiation maneuver ignition at time corresponding to desired maneuver line
		4.	Relative nav
300.0	MC1	5.	Midcourse correction
		6.	Relative nav
540.0	MC2	7.	Midcoure correction
		8.	Relative nav
720.0	MC3	9.	Midcourse correction
		10.	Relative nav
750.7	MC4	7.	Midcoure correction
		8.	Relative nav
760.8	MC5	9.	Midcourse correction
		10.	Relative nav
770.7	STNKP	11.	Establish stationkeeping

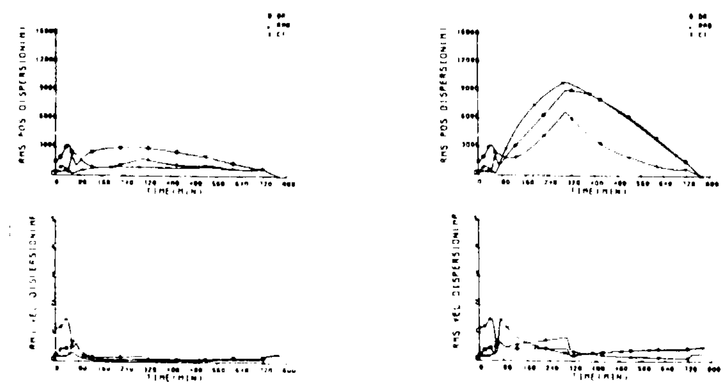
APOAPSE RENDEZVOUS RELATIVE TRAJECTORY XREL VS TIME



APOAPSE RENDEZVOUS RELATIVE TRAJECTORY ZREL VS TIME



APOAPSE RENDEZVOUS RELATIVE DISPERSIONS (1σ) Linear Covariance



APOAPSE RENDEZVOUS NAVIGATION AND TARGETING PERFORMANCE (1σ)

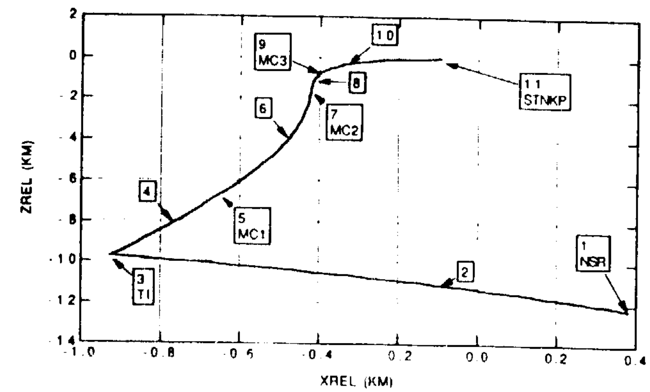
LONG RANGE OPTICAL TRACKING AND SHORT T RANGE (<7 km) RADAR TRACKING

EVENT	RELATIVE NAV ERRORS: (m,mps)						TARGETING ERRORS (mps)			MANEUVER ΔV (mps)	
	POSITION			VELOCITY							
	LOS	IPN	CT	LOS	IPN	CT	LOS	IPN	CT	NOM	1σ
NSR	1309	732	411	0.84	0.84	0.16	-	-	-	-	-
T.I.	1888	69	29	0.36	0.77	0.03	0.00	0.01	0.06	0.29	1.50
MC1	491	15	14	0.01	0.00	0.00	0.02	0.00	0.00	0.00	0.33
MC2	15	12	12	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.23
MC3	11	3	3	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.48
MC4	11	1	1	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.26
MC5	12	0	1	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.20
STNKP	5	11	0	0.00	0.00	0.00	0.00	0.00	0.00	0.42	0.48

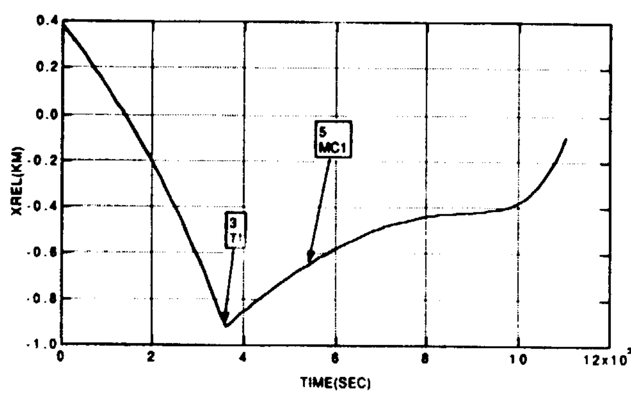
LONG RANGE RADAR TRACKING

EVENT	RELATIVE NAV ERRORS: (m,mps)						TARGETING ERRORS (mps)			MANEUVER ΔV (mps)	
	POSITION			VELOCITY							
	LOS	IPN	CT	LOS	IPN	CT	LOS	IPN	CT	NOM	1σ
NSR	1309	732	411	0.84	0.84	0.16	-	-	-	-	-
T.I.	149	412	491	0.08	0.41	1.09	0.23	0.29	1.67	0.29	2.22
MC1	21	89	73	0.02	0.00	0.01	0.01	0.00	0.00	0.00	1.46
MC2	17	36	29	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.23
MC3	14	7	6	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.48
MC4	14	3	2	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.26
MC5	14	1	1	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.20
STNKP	6	13	0	0.00	0.00	0.00	0.00	0.00	0.00	0.42	0.76

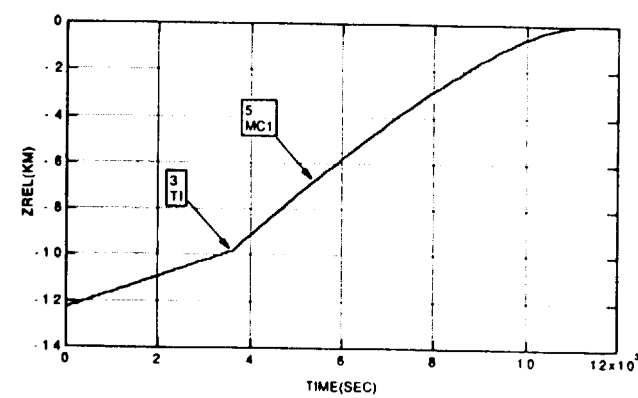
MARS PERIAPSE RENDEZVOUS TRAJECTORY ZREL VS XREL



PERIAPSE RENDEZVOUS TRAJECTORY XREL VS TIME



PERIAPSE RENDEZVOUS TRAJECTORY ZREL VS TIME



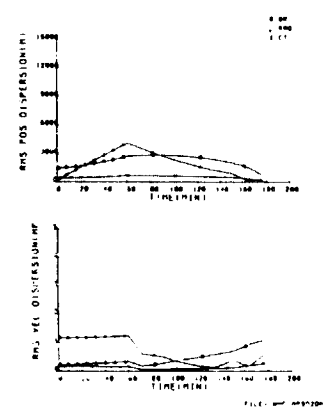
PERIAPSE RENDEZVOUS

TIMELINE

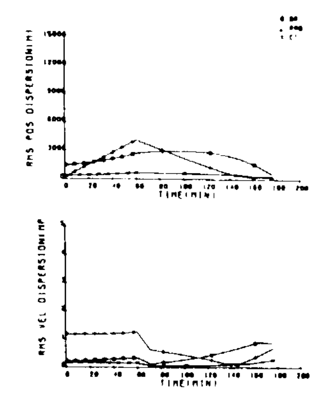
TIME	EVENT		EVENT DESCRIPTIONS
0.0	NSR	1.	Initiate rendezvous phase at coelliptic condition relative to the target
		2.	Relative nav
60.0	T.I.	3.	Transfer initiation maneuver ignition at time corresponding to desired maneuver line
		4.	Relative nav
90.0	MC1	5.	Midcourse correction
		6.	Relative nav
150.0	MC2	7.	Midcoure correction
		8.	Relative nav
165.0	MC3	9.	Midcourse correction
		10.	Relative nav
187.1	STNKP	11.	Establish stationkeeping

PERIAPSE RENDEZVOUS
RELATIVE DISPERSIONS (1σ)
LINEAR COVARIANCE

LONG RANGE OPTICAL TRACKING
SHORT RANGE (<7 km) RADAR TRACKING



LONG RANGE RADAR TRACKING



PERIAPSE RENDEZVOUS NAVIGATION AND TARGETING PERFORMANCE (1σ)

LONG RANGE OPTICAL TRACKING AND SHORT T RANGE (<7 km) RADAR TRACKING

EVENT	RELATIVE NAV ERRORS: (m,mps) POSITION			VELOCITY			TARGETING ERRORS (mps)			MANEUVER ΔV (mps)	
	LOS	IPN	CT	LOS	IPN	CT	LOS	IPN	CT	NOM	1σ
NSR	1074	1048	411	0.56	1.05	0.16	-	-	-	-	-
T.I.	718	5	5	0.19	0.00	0.00	0.11	0.04	0.00	1.25	1.97
MC1	81	4	3	0.18	0.01	0.00	0.16	0.00	0.00	0.00	0.22
MC2	11	4	4	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.77
MC3	12	2	2	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.17
STNKP	11	2	0	0.00	0.00	0.00	0.00	0.01	0.00	0.53	1.26

LONG RANGE RADAR TRACKING

EVENT	RELATIVE NAV ERRORS: (m,mps) POSITION			VELOCITY			TARGETING ERRORS (mps)			MANEUVER ΔV (mps)	
	LOS	IPN	CT	LOS	IPN	CT	LOS	IPN	CT	NOM	1σ
NSR	1074	1048	411	0.56	1.05	0.16	-	-	-	-	-
T.I.	29	172	171	0.02	0.01	0.01	0.02	0.01	0.01	1.25	1.97
MC1	16	117	118	0.01	0.02	0.02	0.02	0.01	0.01	0.00	0.14
MC2	13	27	28	0.01	0.02	0.02	0.01	0.01	0.01	0.00	0.32
MC3	15	12	13	0.00	0.01	0.01	0.02	0.01	0.01	0.00	0.18
STNKP	13	2	0	0.00	0.00	0.00	0.00	0.01	0.00	0.53	1.09

SUMMARY

- Initial Mars rendezvous performance results show the following:
  - Nav performance with long range optics and short range radar of shuttle quality provides small maneuver targeting errors for the Mars rendezvous profiles studied
  - Dispersion ellipse at the prox ops initiation points are within mission design limits

PROXIMITY OPERATIONS PERFORMANCE RESULTS FOR CANDIDATE AR&D SYSTEMS

CSDL

PROXIMITY OPERATIONS ANALYSIS AREAS

- IGN&C system operations
- IGN&C system transport delays
- Inter-relationship between nav thresholds, nav accuracy, and trajectory control algorithm
- Phasing between navigation and "trajectory control" guidance
- G&N algorithm rates and gains (where applicable)
- Failed/degraded sensor operation
- IMU accelerometer and gyro errors
- Laser sensor errors
- Relative nav using both Kalman filter and deterministic nav
- Target attitude estimation accuracy, using both Kalman filter and deterministic nav (thus allowing relative attitude determination)
- Trajectory control techniques and effect on plume impingment of the target (for Space Station buildup configurations), fuel usage and contingency recovery capabilities
- Finite target effects: offset docking ports, target attitude motion, etc.
- Unmodeled errors

PROXIMITY OPERATIONS PERFORMANCE FIGURES OF MERIT

- System level
  - Resultant 3σ docking conditions
  - Mission design capabilities
- Subsystem level
  - System performance capability with degraded and failed sensors
  - Sensitivity to maneuver execution errors and effector failures
  - Dispersion handling capabilities at start of rendezvous phase
  - Fuel usage
  - Approach profile integrity
    - Dispersions at critical maneuver points
    - "integrity" of approach profile
  - Failure identification, reconfiguration and recovery
  - Applicability of subsystem design to a "generic" AR&D system
  - Normal, contingency and stress case performance
  - Plume impingement and contamination of the target

SUMMARY OF INITIAL NAVIGATION PERFORMANCE STUDY

- An initial study was made to assess nav system design modifications for prox ops, above that of just adding the Laser nav capability
- Detailed results will not be presented, but the following is a summary of the analysis
  - — During proximity operations, the velocity thresholds for incorporating IMU data are set to zero
    - This involves a tradeoff between incorporating IMU accelerometer bias and sensing translation maneuvers
    - Sensing the maneuvers provides faster relative error resolution if maneuver are above the bias values
    - Laser nav corrects state error which results from incorporates the bias
  - — Process noise of 1.0 fps is added directly to the nav filter position error covariance, to account for RCS jet firings occurring between nav measurement cycles of 8 seconds
    - Editing of Laser measurements may occur if this is not done
  - — Kalman filter proccessing of Laser measurements versus relative state determination from the measurements
    - Deterministic solution is adversely effected by sensor random errors and has degraded velocity estimation when RCS firings occur between
    - Kalman filter processing:
      - — Smooths random errors
      - — Performance can be degraded with large IMU accelerometer bias but these can be estimated

APPROACH PROFILE DISCUSSION

- Two approach profiles are being used in the analysis
  - — "Straight in" approach along the target leading VBAR
  - — A two phase trajectory approach combining a "double cusp" type targeting scheme. Profile is designed as follows:
    - The second phase of the trajectory is targeted to a cm to cm relative offset, such that the active and target vehicle docking ports are aligned, and with a final cm to cm closing rate of 0.1 fps
    - A one revolution backwards integration from this desired cm to cm condition defines the end point of the first portion of the trajectory
    - A further one revolution flyback from this first to second phase transition point defines the starting conditions of the profile

TRAJECTORY CONTROLLERS

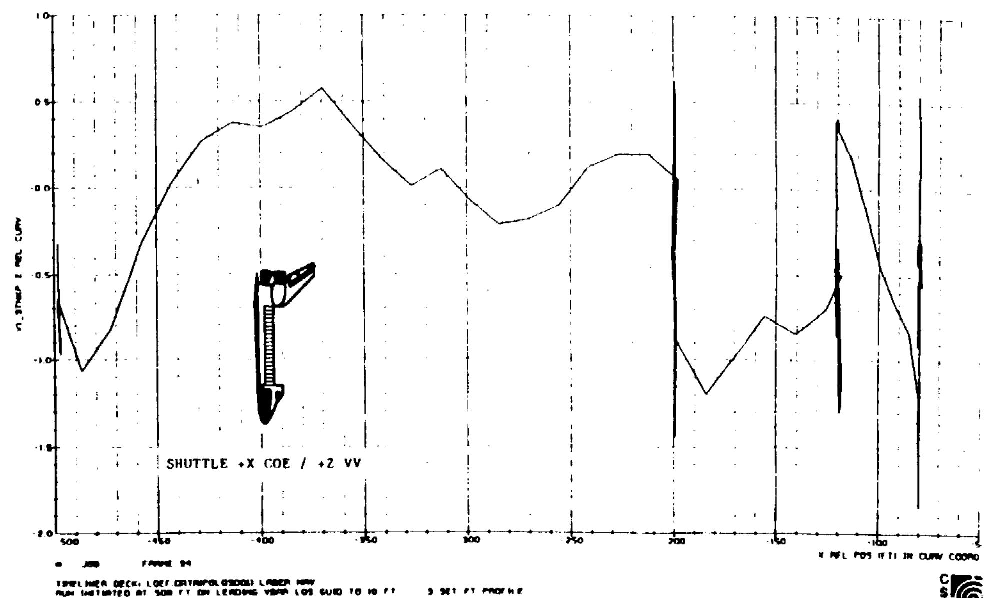
- Two <u>trajectory controllers</u> are being used in the analysis
  - — Linear quadratic regulator for the VBAR approach profile
    - Approach initiated at 500 ft on the leading VBAR following a standard Shuttle rendezvous with prox ops being initiated at MCC4
    - Shuttle cm to Station cm approach
    - Following approach schedule is used:
      - — 500 ft to 200 ft at 1.0 fps with a 2 ft position deadband
      - — 200 ft to 120 ft at 1.0 fps with a 2 ft position deadband
      - — 120 to 80 ft at 0.5 fps with a 2 ft position deadband

- Guided VBAR controller for the dual segment profile ("guided" VBAR)
  - — Proximity operations phase is initiated at 5000 ft from the target after crossing the target leading VBAR, following the long range rendezvous profile discussed earlier
  - — A midcourse maneuver is executed following the VBAR crossing to control the arrival at the start condition for the first segment of the profile

C-2

LINEAR QUADRATIC REGULATOR: VBAR APPROACH

CASE L1: - Baseline AR&D System
- No plume on target



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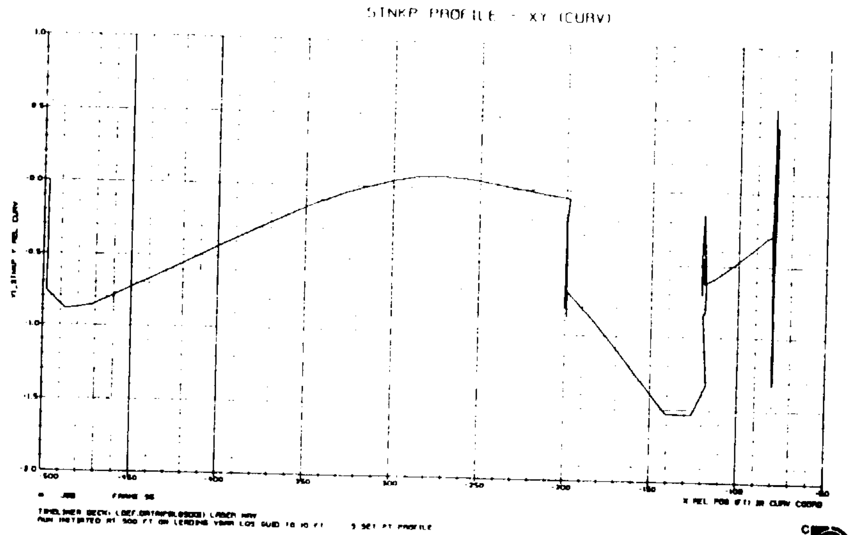
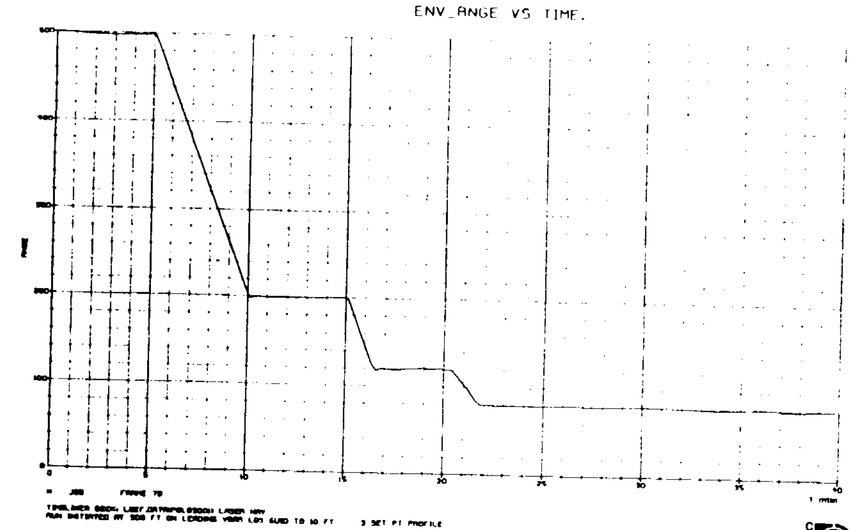
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L1:
- **Baseline AR&D System**
- **No plume on target**



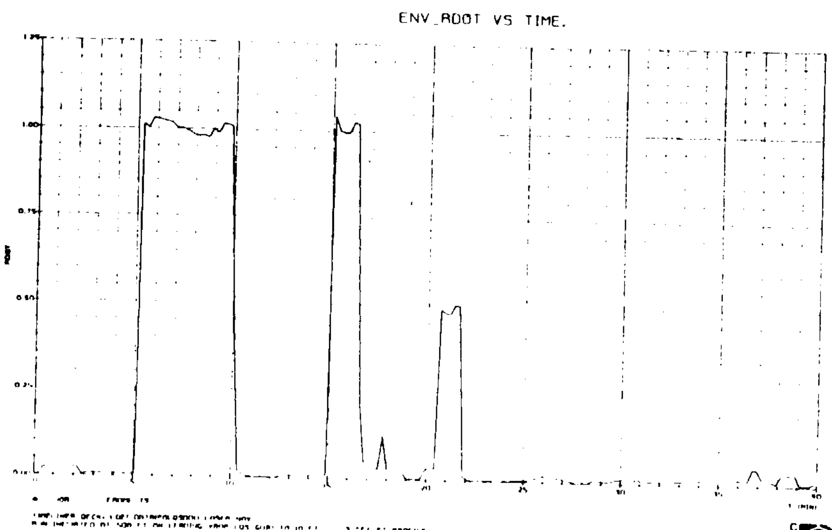
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L1:
- **Baseline AR&D System**
- **No plume on target**



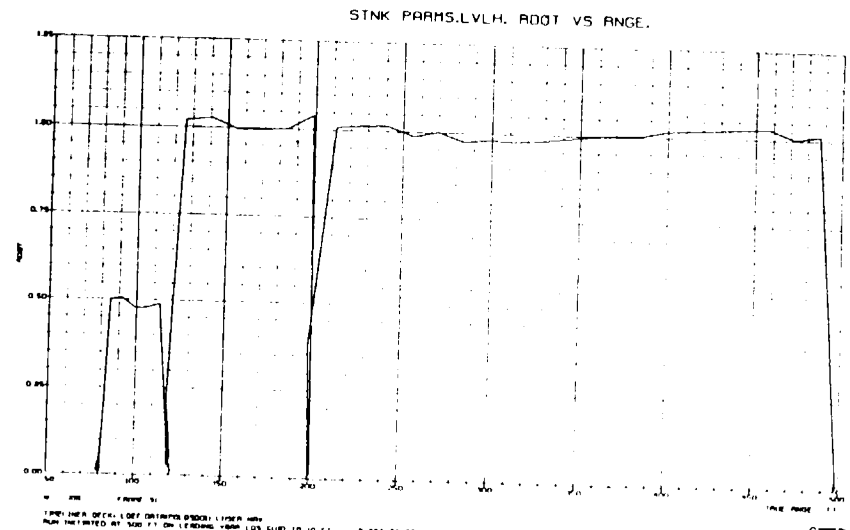
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L1:
- **Baseline AR&D System**
- **No plume on target**



LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L1:
- **Baseline AR&D System**
- **No plume on target**



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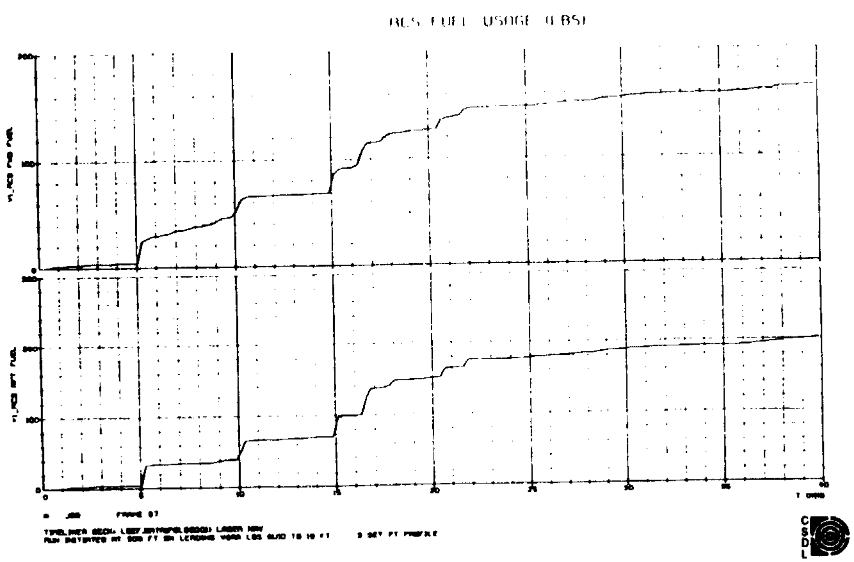
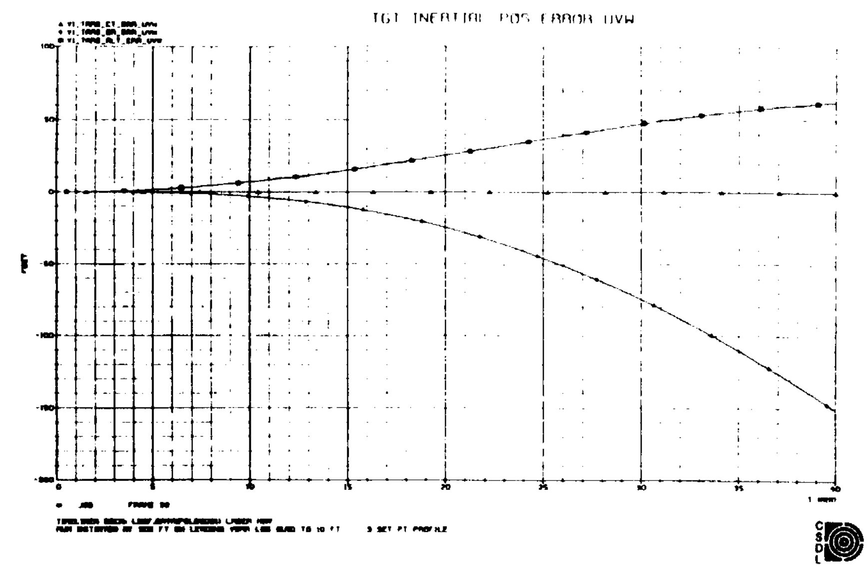
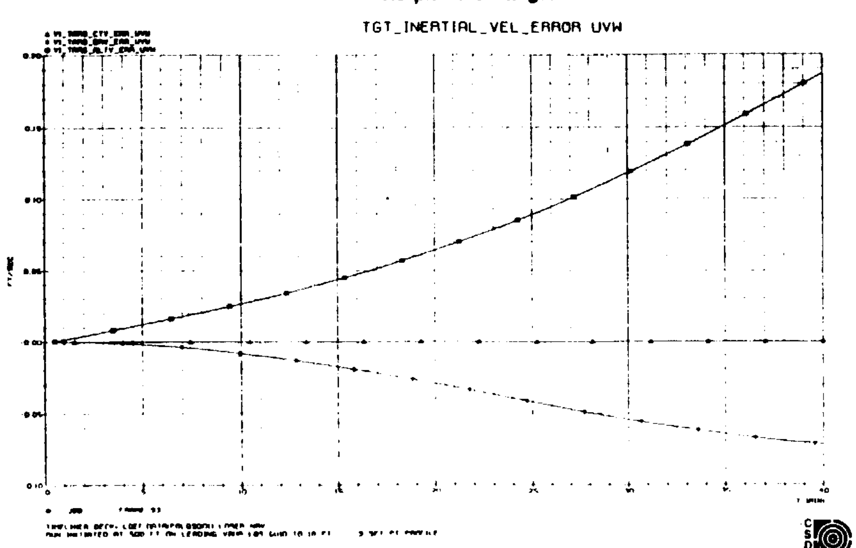
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)
CASE L1: - **Baseline AR&D System**
- **No plume on target**



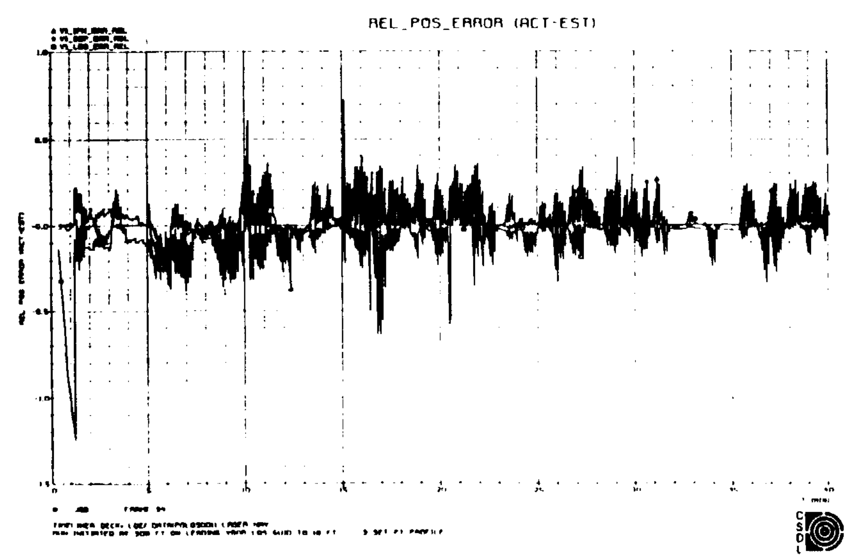
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)
CASE L1: - **Baseline AR&D System**
- **No plume on target**



LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)
CASE L1: - **Baseline AR&D System**
- **No plume on target**

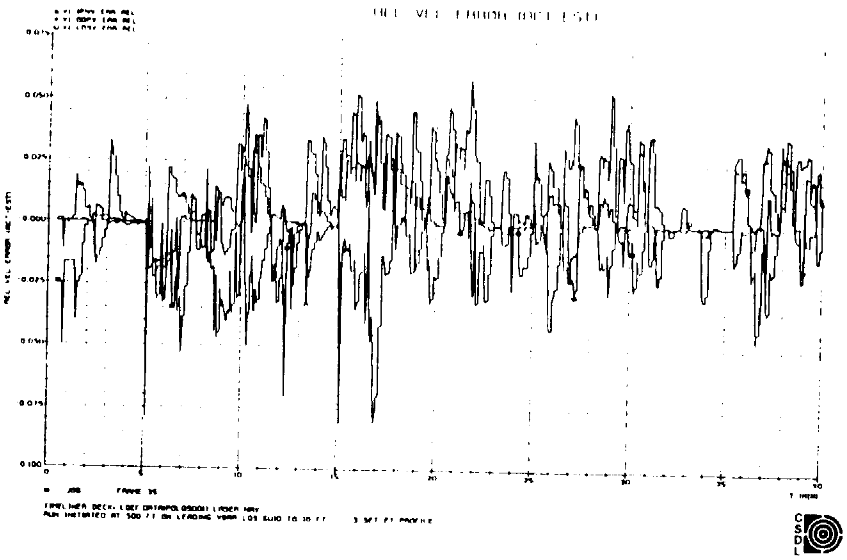


LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)
CASE L1: - **Baseline AR&D System**
- **No plume on target**



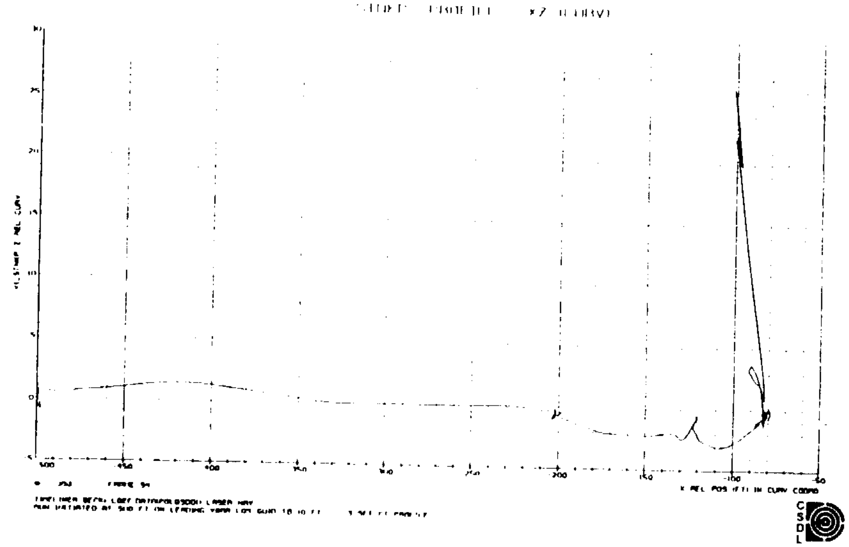
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L1:
- Baseline AR&D System
- No plume on target



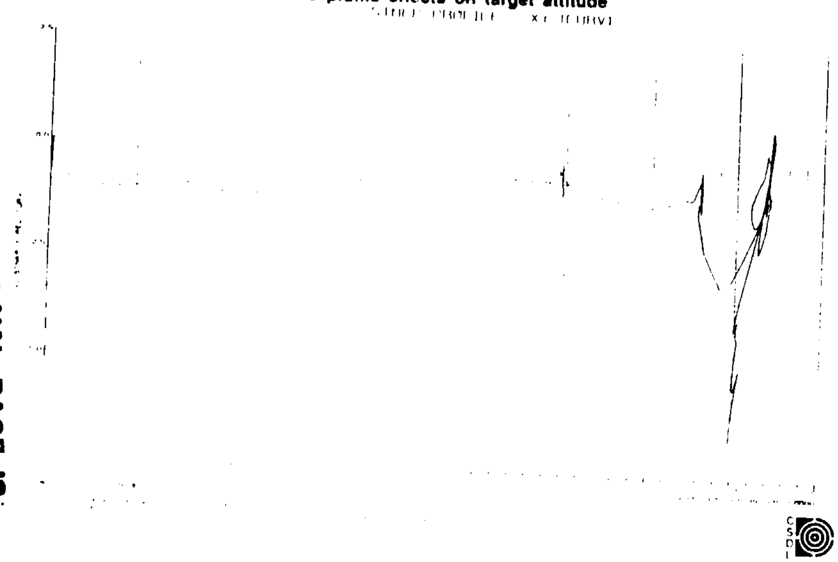
LINEAR QUADRATIC REGULATOR: VBAR APPROACH

CASE L2:
- Baseline AR&D System
- Plume effects on target translation
- No plume effects on target attitude



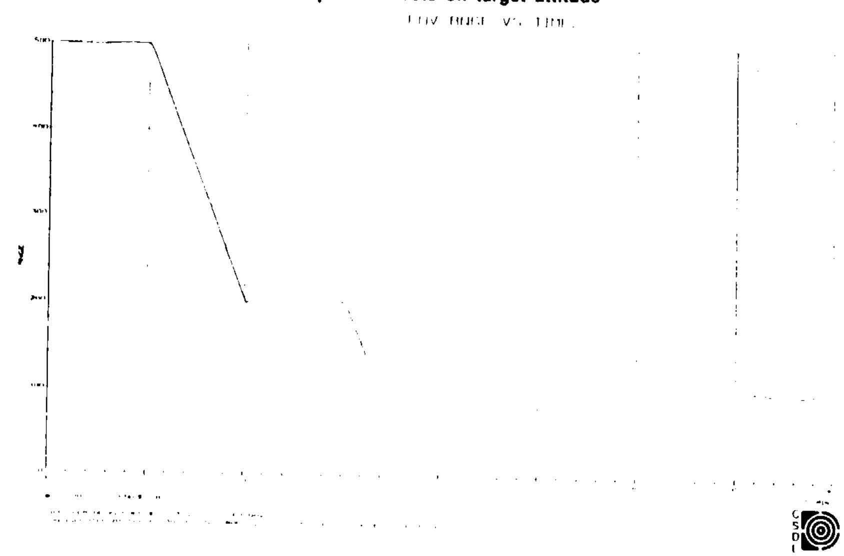
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L2:
- Baseline AR&D System
- Plume effects on target translation
- No plume effects on target attitude



LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L2:
- Baseline AR&D System
- Plume effects on target translation
- No plume effects on target attitude



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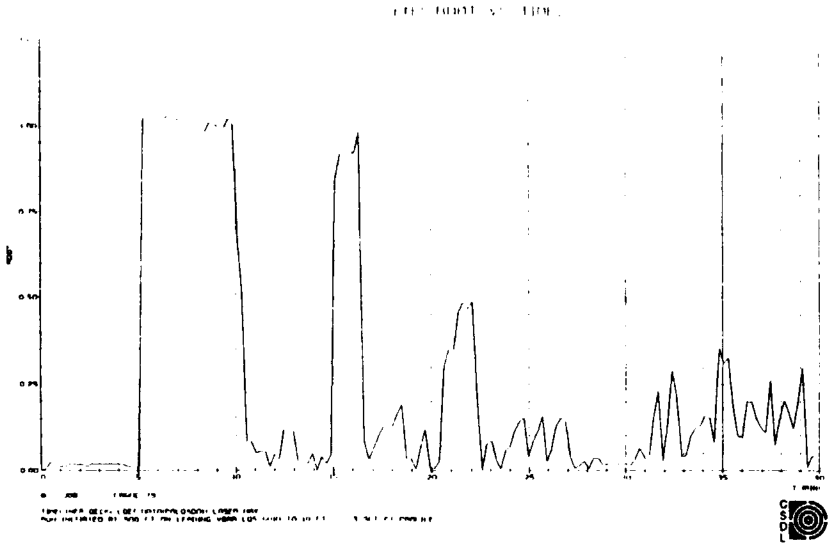
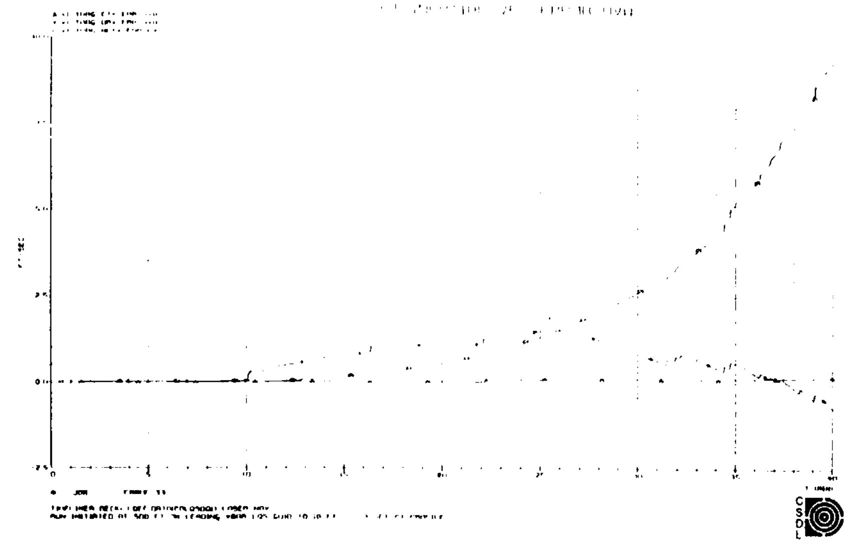
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L2:
- Baseline AR&D System
- Plume effects on target translation
- No plume effects on target attitude



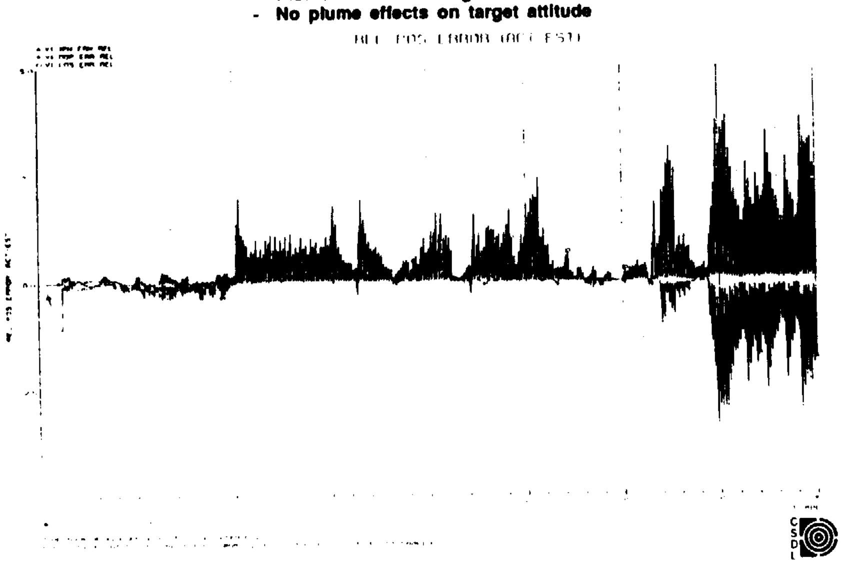
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L2:
- Baseline AR&D System
- Plume effects on target translation
- No plume effects on target attitude



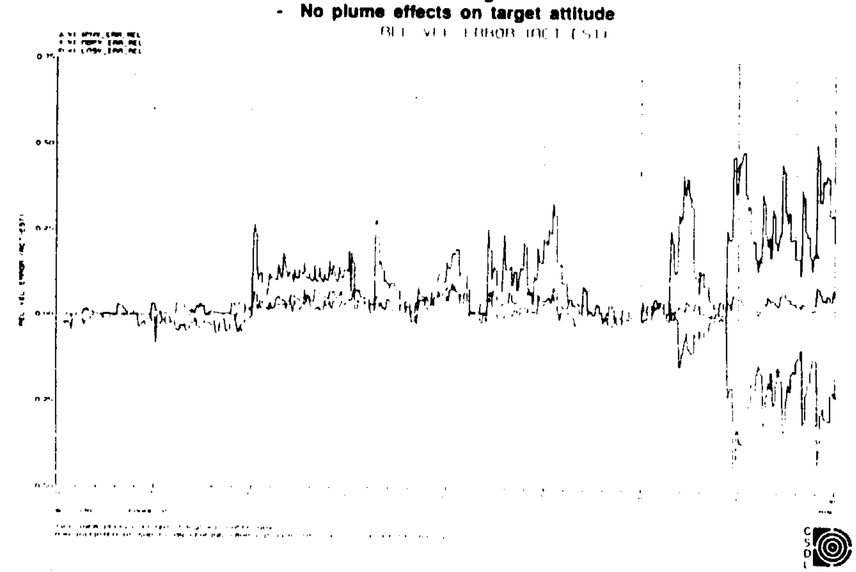
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L2:
- Baseline AR&D System
- Plume effects on target translation
- No plume effects on target attitude



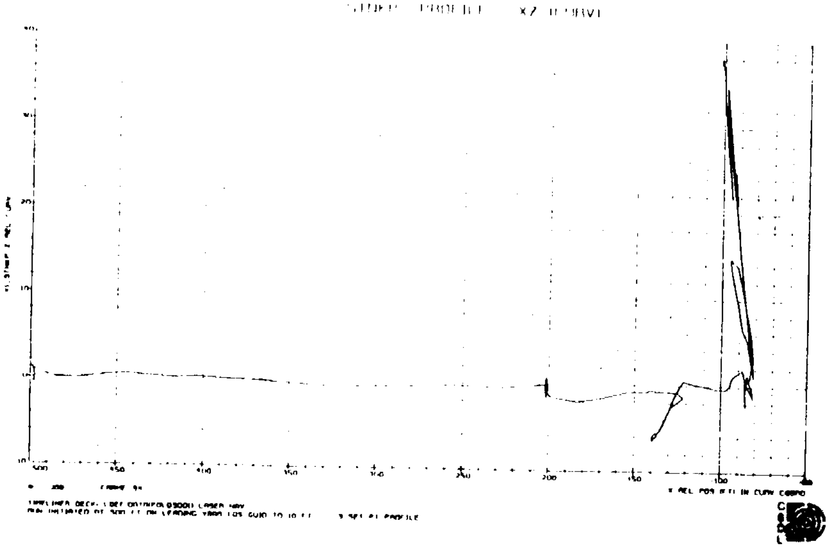
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L2:
- Baseline AR&D System
- Plume effects on target translation
- No plume effects on target attitude



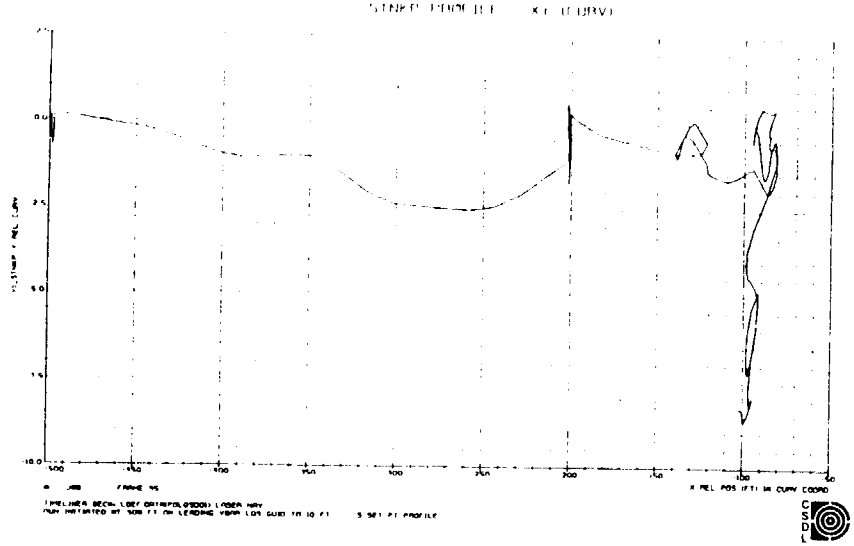
LINEAR QUADRATIC REGULATOR: VBAR APPROACH

CASE L3:
- Baseline AR&D System
- 6 DOF target
- Plume effects on target translation and attitude



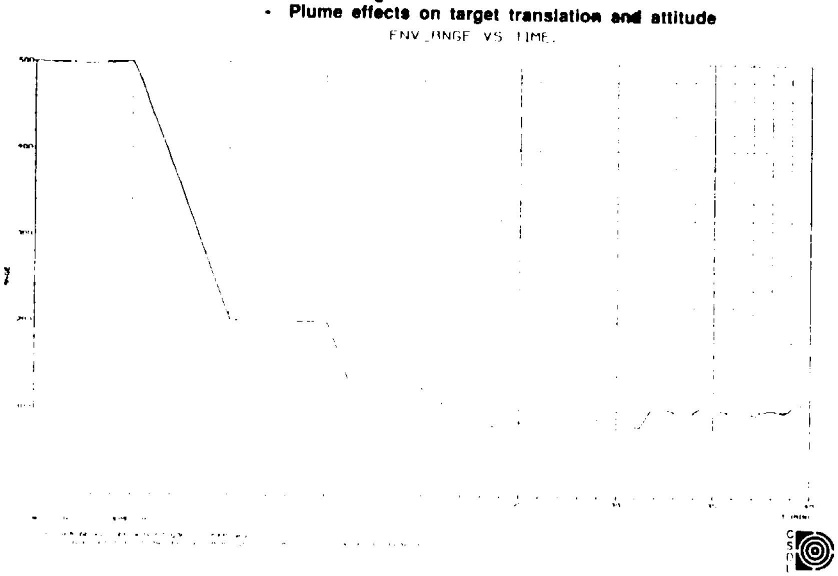
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L3:
- Baseline AR&D System
- 6 DOF target
- Plume effects on target translation and attitude



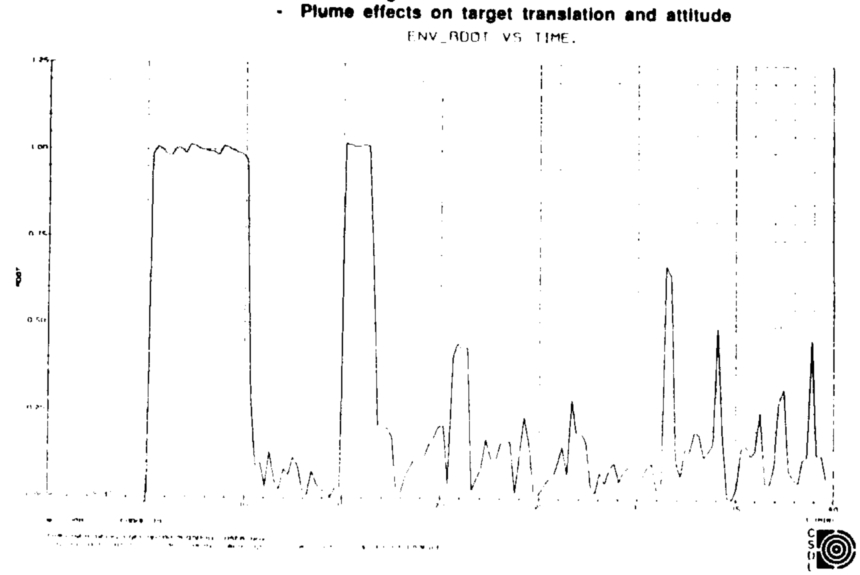
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L3:
- Baseline AR&D System
- 6 DOF target
- Plume effects on target translation and attitude



LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L3:
- Baseline AR&D System
- 6 DOF target
- Plume effects on target translation and attitude



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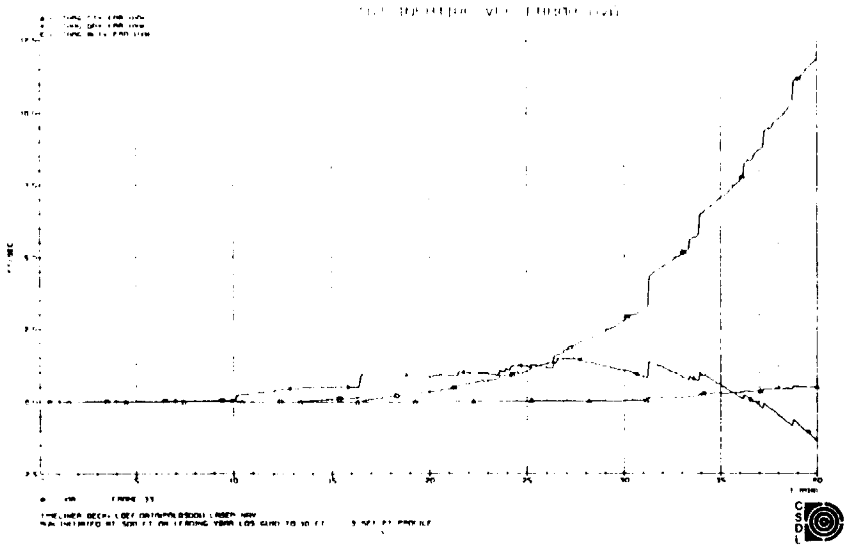
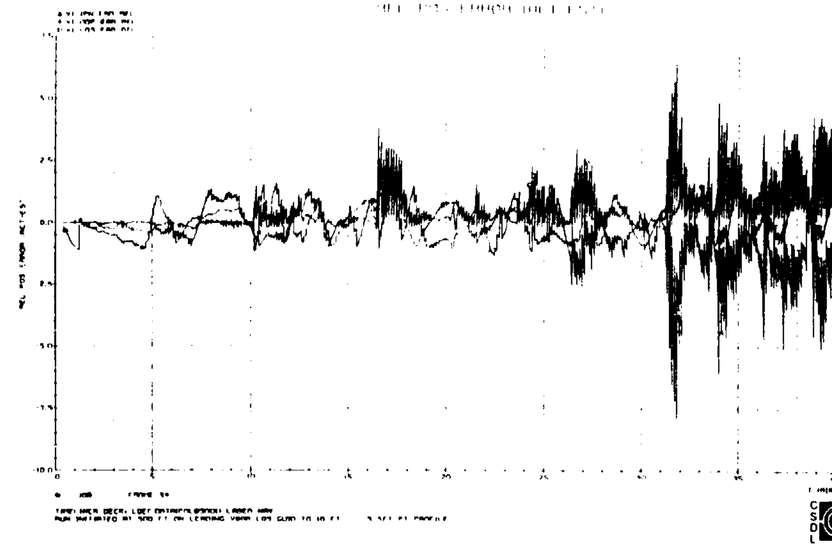
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L3:
- Baseline AR&D System
- 6 DOF target
- Plume effects on target translation and attitude



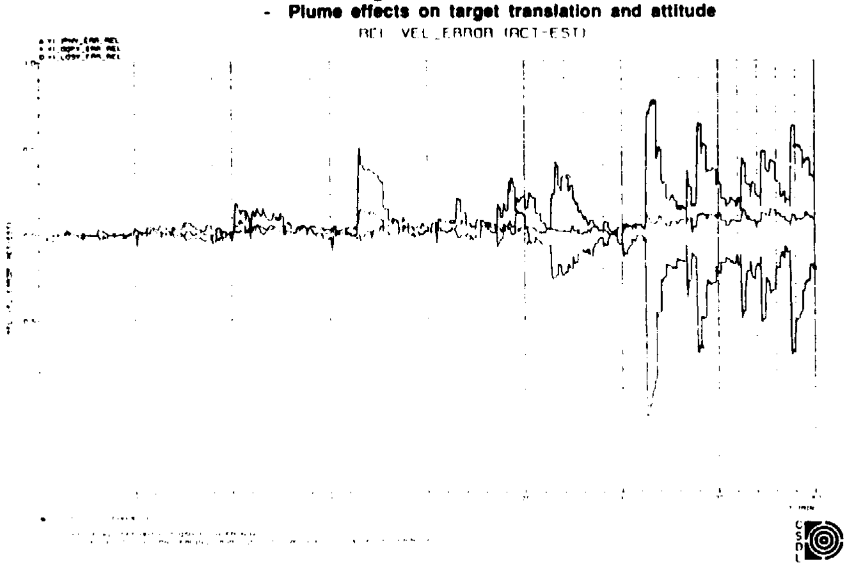
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L3:
- Baseline AR&D System
- 6 DOF target
- Plume effects on target translation and attitude



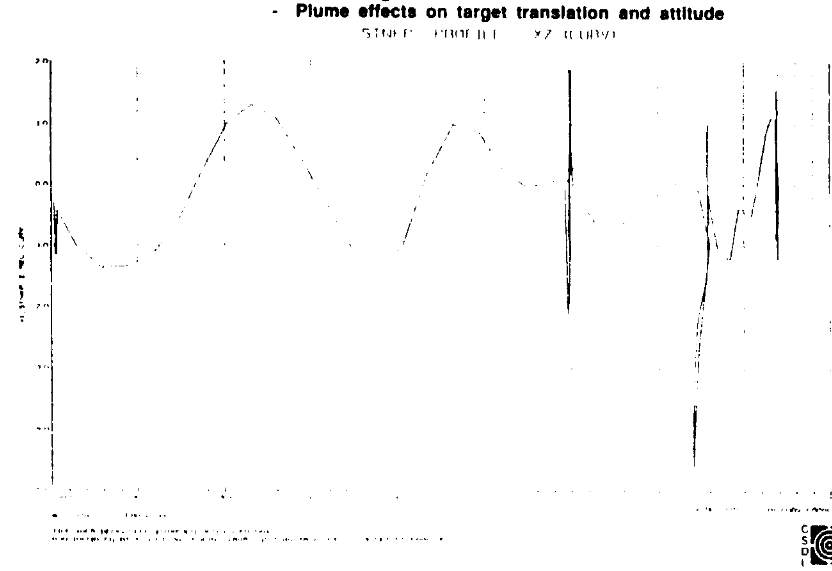
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L3:
- Baseline AR&D System
- 6 DOF target
- Plume effects on target translation and attitude



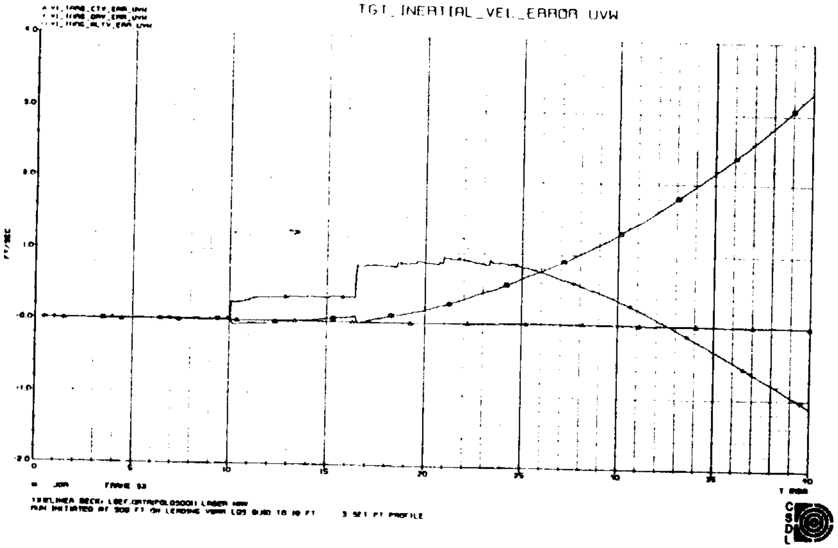
LINEAR QUADRATIC REGULATOR: VBAR APPROACH

CASE L4:
- Baseline AR&D System with Nav Rate at 1 sec
- 6 DOF target
- Plume effects on target translation and attitude



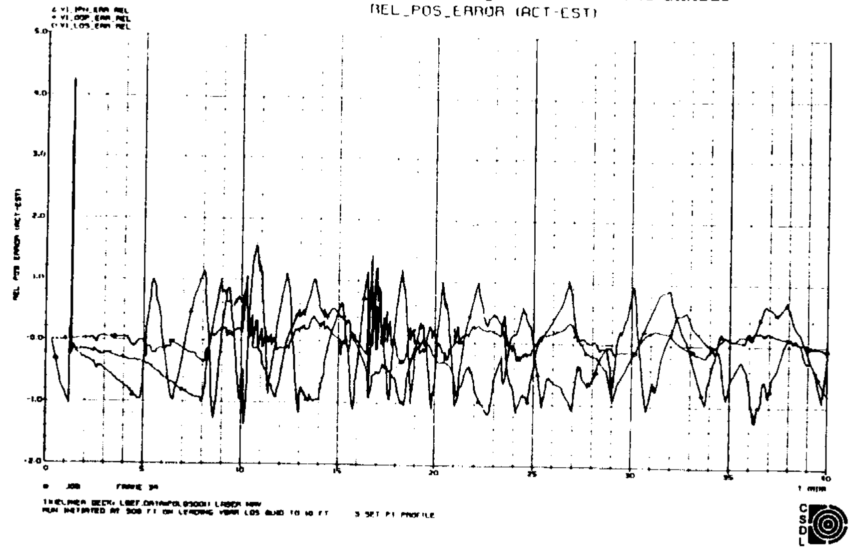
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L4:
- **Baseline AR&D System with Nav Rate at 1 sec**
- **6 DOF target**
- **Plume effects on target translation and attitude**



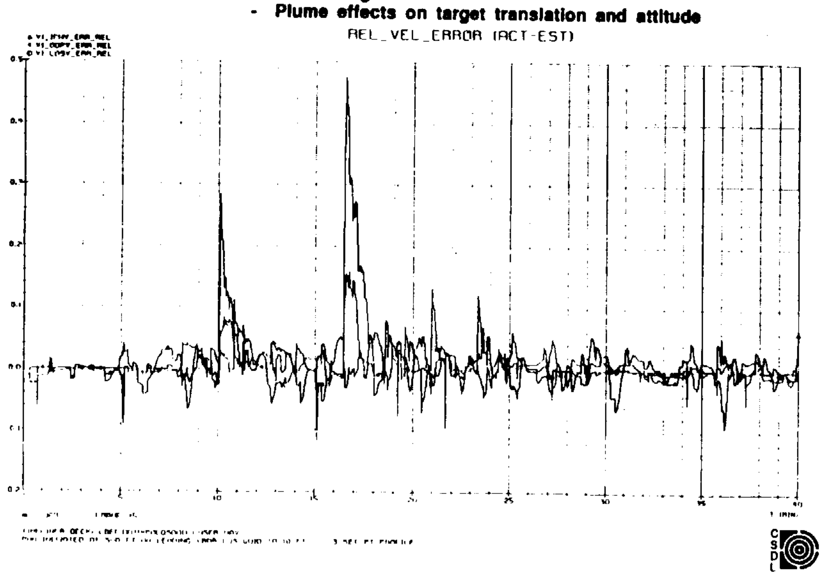
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L4:
- **Baseline AR&D System with Nav Rate at 1 sec**
- **6 DOF target**
- **Plume effects on target translation and attitude**



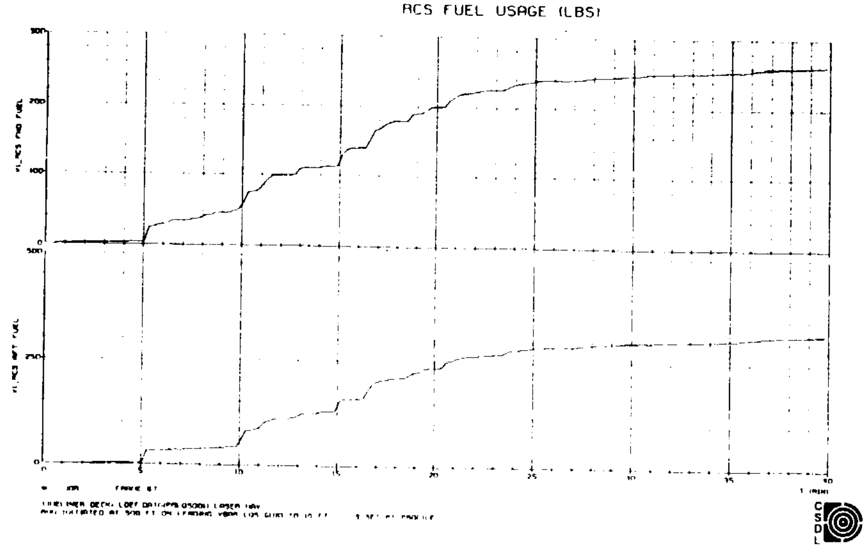
LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L4:
- **Baseline AR&D System with Nav Rate at 1 sec**
- **6 DOF target**
- **Plume effects on target translation and attitude**



LINEAR QUADRATIC REGULATOR: VBAR APPROACH (continued)

CASE L4:
- **Baseline AR&D System with Nav Rate at 1 sec**
- **6 DOF target**
- **Plume effects on target translation and attitude**



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VBAR APPROACH PROFILE USING LINEAR QUADRATIC REGULATOR

SUMMARY OF RESULTS

TEST CASE	NAV RATE	TGT VEHICLE LVLH ATT HOLD		PLUME EFFECT ON TARGET		SUMMARY OF RESULTS
		3 DOF	6 DOF	NO	YES	
L1	Baseline 8 s	X		X		— Desired corridor about the VBAR maintained — Good IGN&C system performance
L2	8 sec	X			X	— Large plume effects on target — Performance approaching 80 ft stationkeeping point is good — 80 ft position is NOT maintained due to a large plume hit on the target — Nav rate precludes resolution of relative state change fast enough, for effective controller response
L3			X		X	— Performance with 6 DOF target essentially the same as with 3 DOF target — System cannot maintain 80 ft relative offset
L4	1		X		X	— Increasing the nav rate upon approach to 80 ft, permits the rapid resolution of the relative state change due to the plume effects on the target — This allows the trajectory controller to target the necessary maneuver correction to maintain the relative stationkeeping position — Good system performance

VBAR APPROACH PROFILE USING LINEAR QUADRATIC REGULATOR

SUMMARY OF RESULTS (cont'd)

- From additional simulation results not shown
  - — Need to increase the nav filter residual edit I-load (or increase covariance position process noise) due to effects of plume on the target state
    - Relative state changes due to plume are not modeled.
    - Appears as a measurement residual which filter treats as a sensor error out of specification
  - — Adverse effect on performance with uncertainty in location of target reflectors relative to the target center of mass
    - Appears as a "bias" to the nav filter
    - Analysis in work to solve this problem

VBAR APPROACH PROFILE USING LINEAR QUADRATIC REGULATOR
SUMMARY OF RESULTS

TEST CASE	NAV RATE	TGT VEHICLE LVLH ATT HOLD		PLUME EFFECT ON TARGET		SUMMARY OF RESULTS
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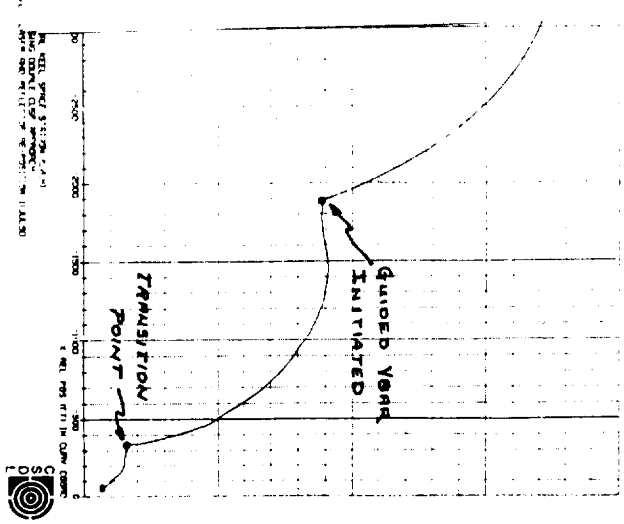
II

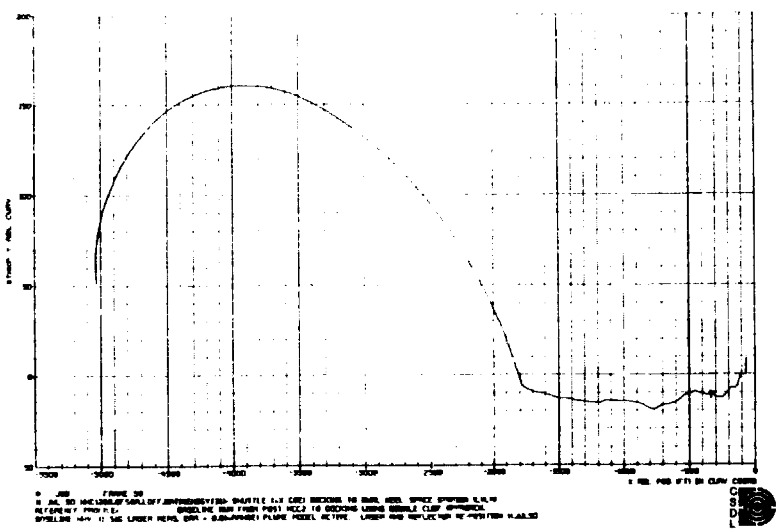
AR APPROACH
ine AR&D System
plume effect on heavv target
P PROFILE - XZ (CURV)



GUIDED VBAR APPROACH (continued)

CASE G1: - Baseline AR&D System

- With plume effect on heavy target

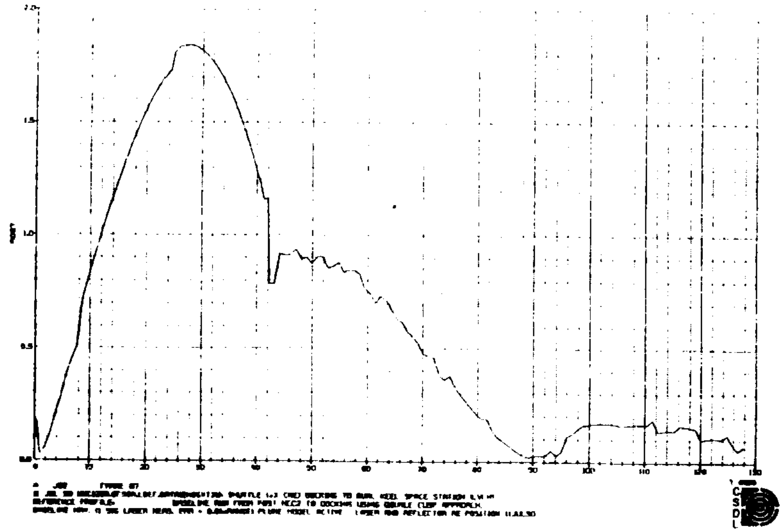


GUIDED VBAR APPROACH (continued)

CASE G1: - Baseline AR&D System

- With plume effect on heavy target

ENV_RDOT VS TIME.

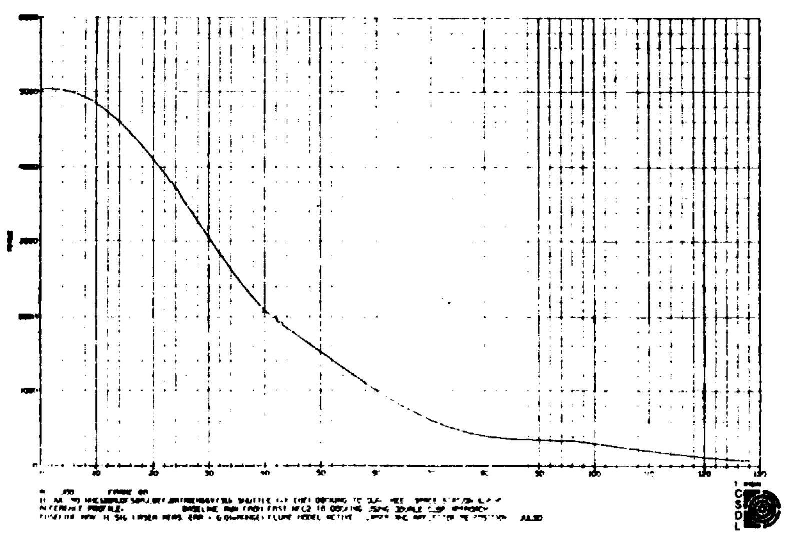


GUIDED VBAR APPROACH (continued)

CASE G1: - Baseline AR&D System

- With plume effect on heavy target

ENV_RNGE VS TIME.

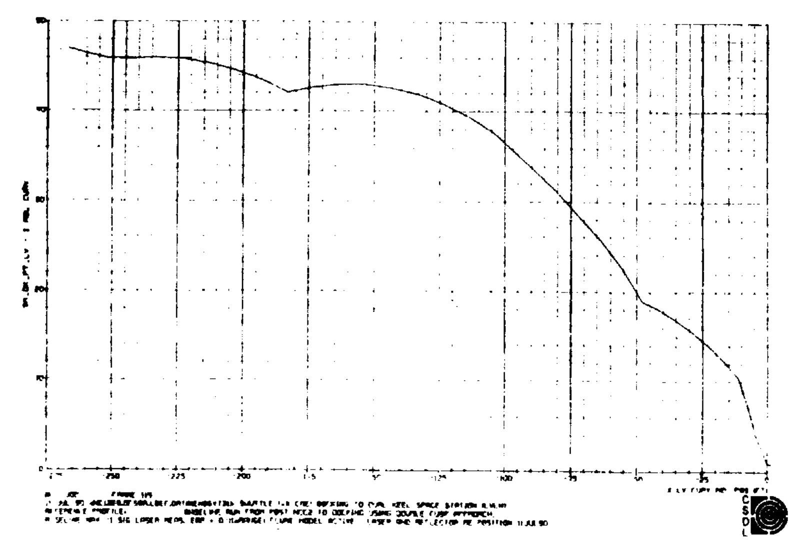


GUIDED VBAR APPROACH (continued)

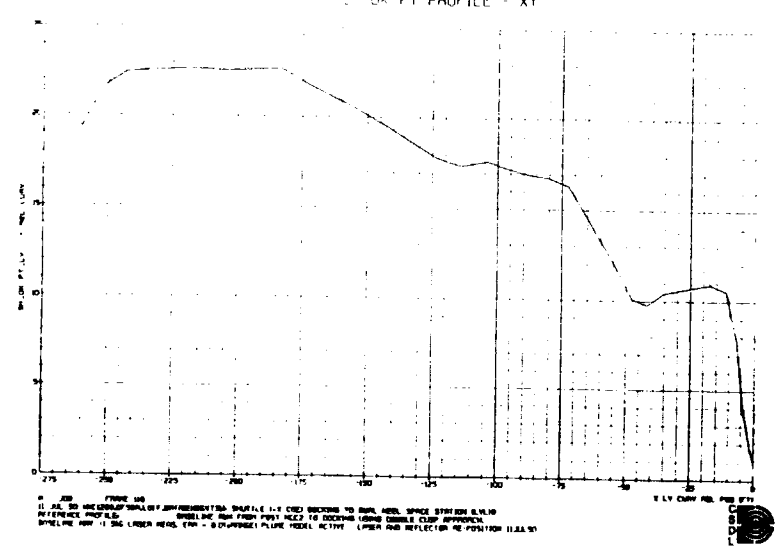
CASE G1: - Baseline AR&D System

- With plume effect on heavy target

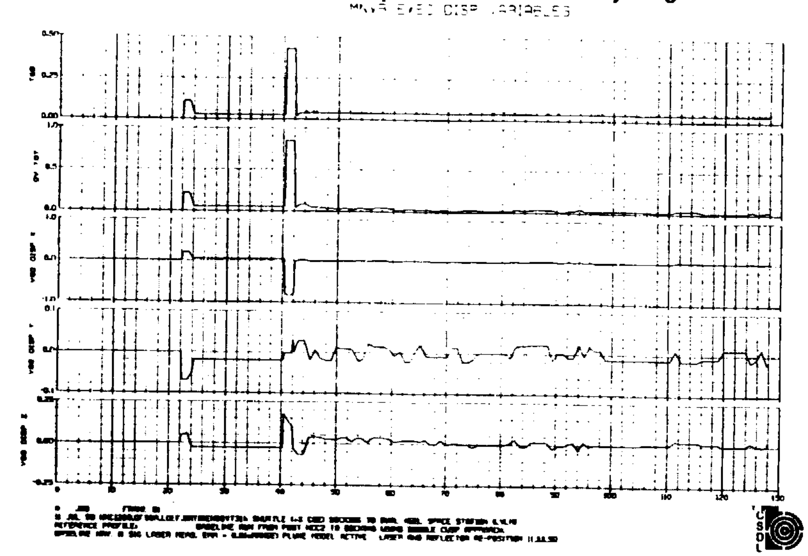
SH DK PT PROFILE - XZ



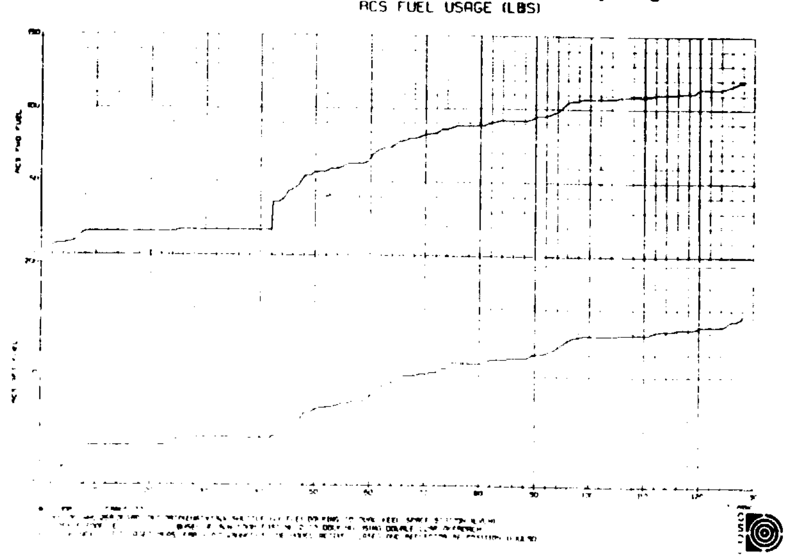
GUIDED VBAR APPROACH (continued)
CASE G1: - Baseline AR&D System
- With plume effect on heavy target



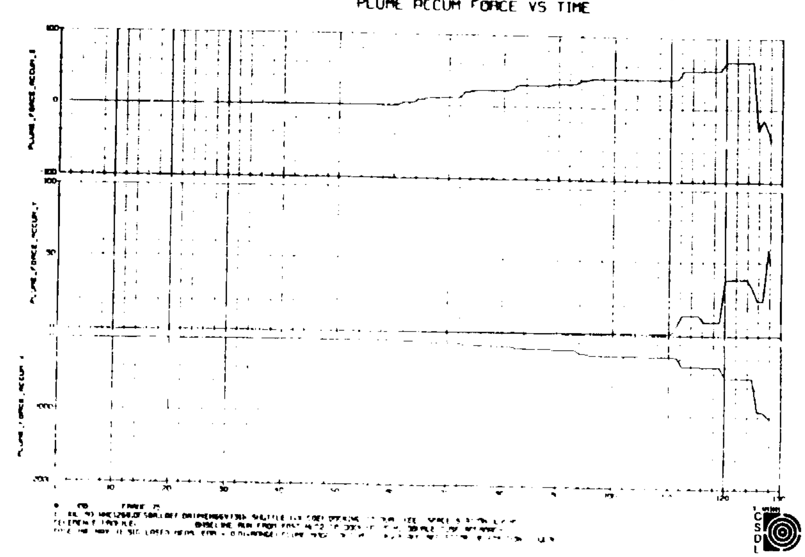
GUIDED VBAR APPROACH (continued)
CASE G1: - Baseline AR&D System
- With plume effect on heavy target



GUIDED VBAR APPROACH (continued)
CASE G1: - Baseline AR&D System
- With plume effect on heavy target



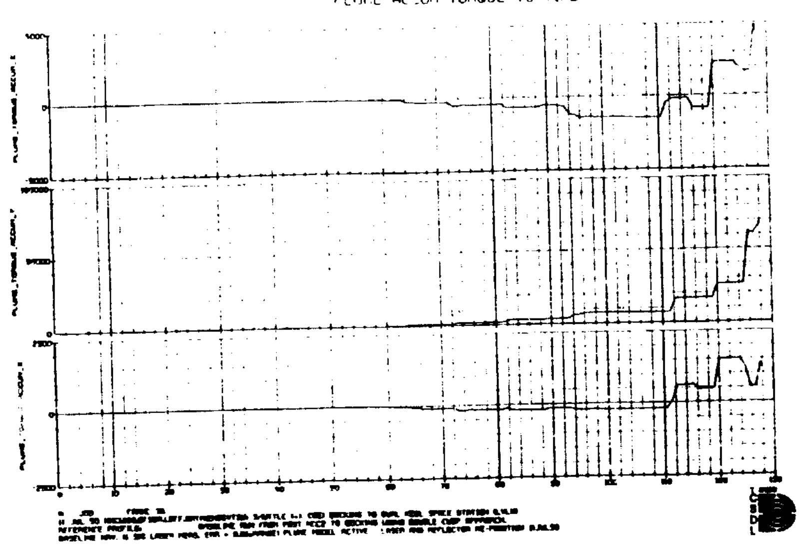
GUIDED VBAR APPROACH (continued)
CASE G1: - Baseline AR&D System
- With plume effect on heavy target



GUIDED VBAR APPROACH (continued)

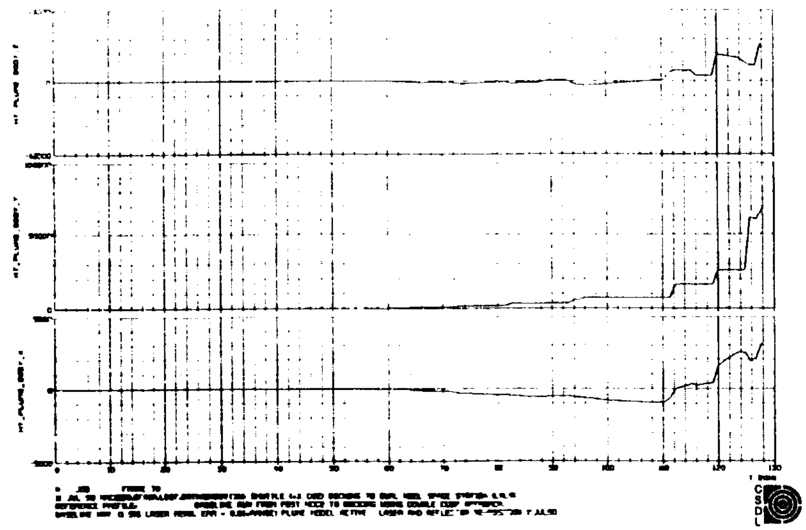
CASE G1: - Baseline AR&D System
- With plume effect on heavy target

PLUME ACCUM TORQUE VS TIME



GUIDED VBAR APPROACH (continued)

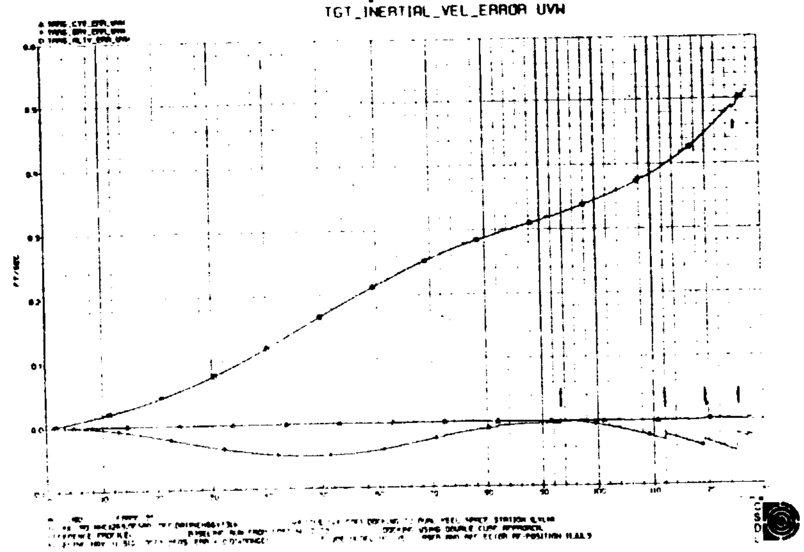
CASE G1: - Baseline AR&D System
- With plume effect on heavy target



GUIDED VBAR APPROACH (continued)

CASE G1: - Baseline AR&D System
- With plume effect on heavy target

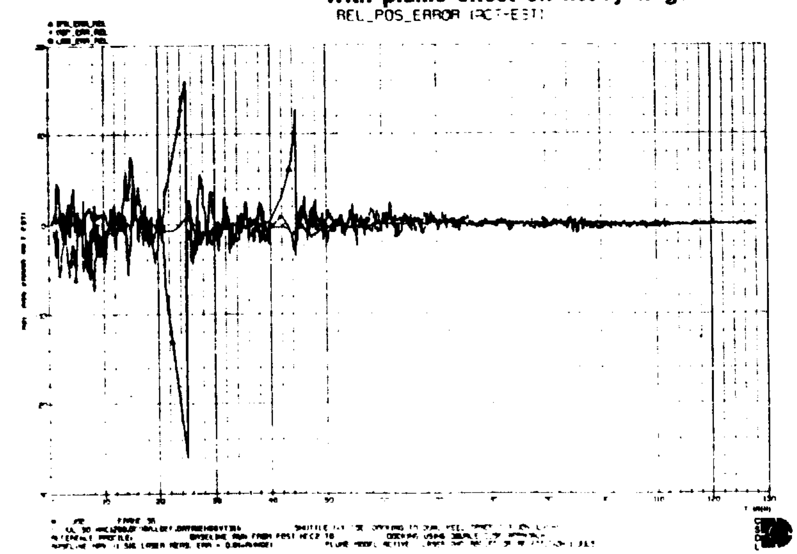
TGT_INERTIAL_VEL_ERROR UVW



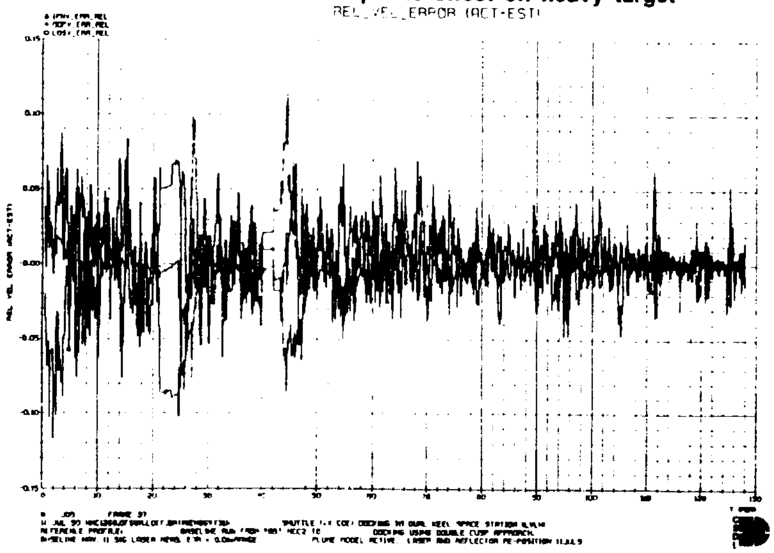
GUIDED VBAR APPROACH (continued)

CASE G1: - Baseline AR&D System
- With plume effect on heavy target

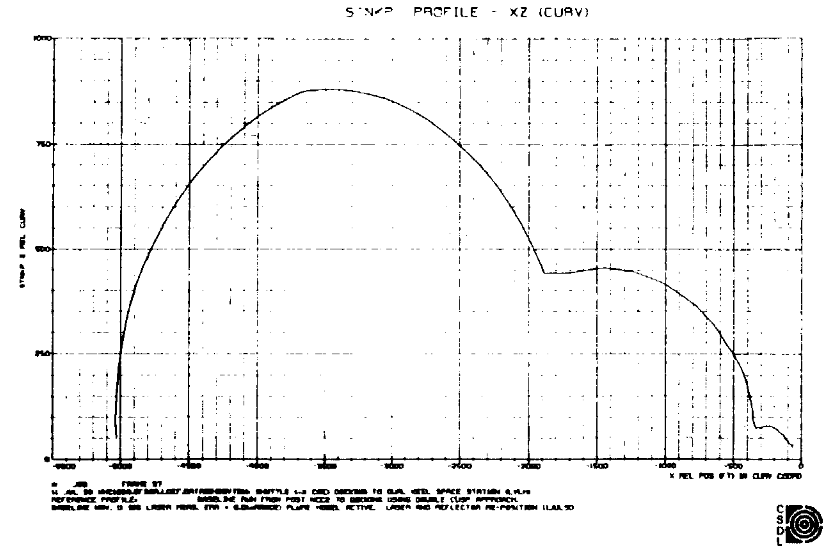
REL_POS_ERROR



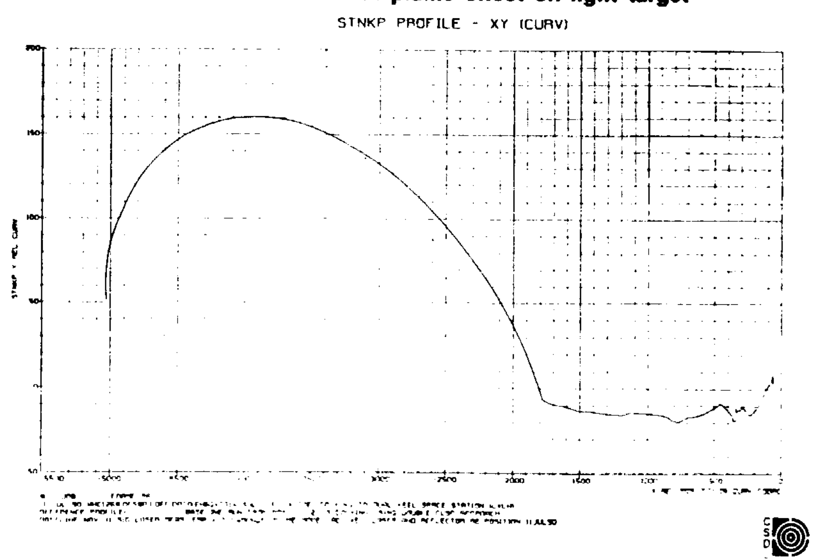
GUIDED VBAR APPROACH (continued)
CASE G1: - Baseline AR&D System
- With plume effect on heavy target



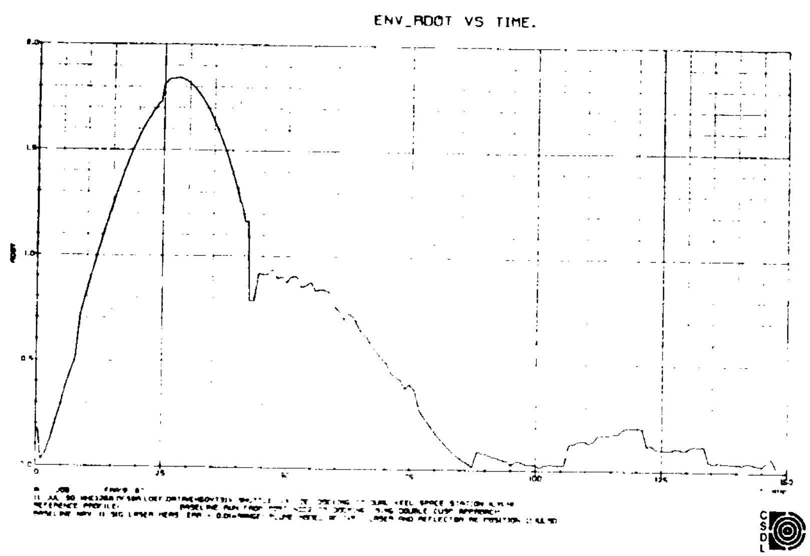
GUIDED VBAR APPROACH
CASE G2: - Baseline AR&D System
- With plume effect on light target



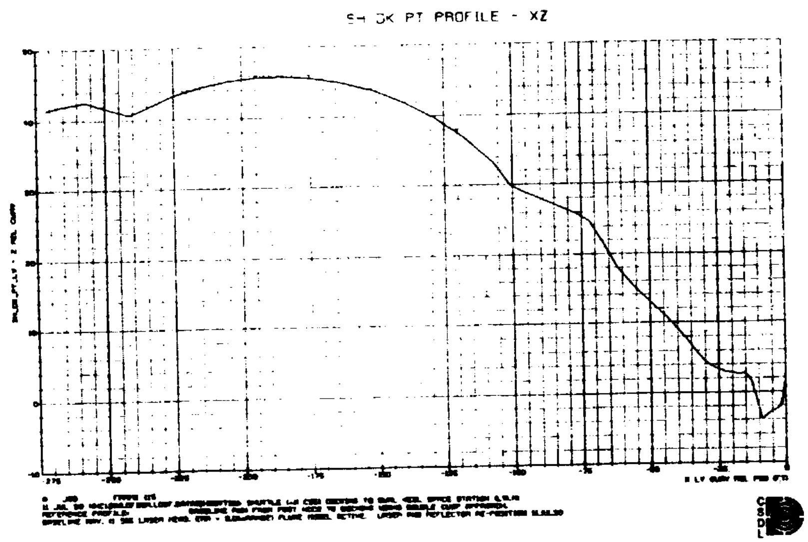
GUIDED VBAR APPROACH (continued)
CASE G2: - Baseline AR&D System
- With plume effect on light target



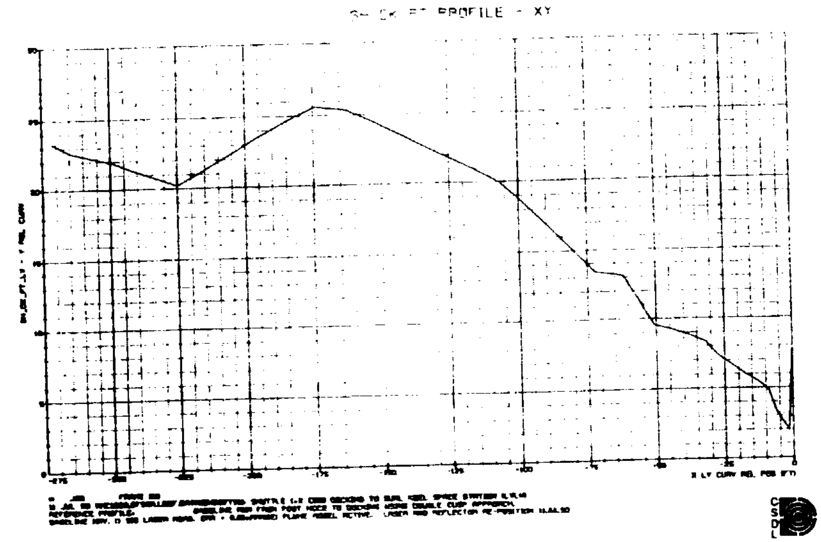
GUIDED VBAR APPROACH (continued)
CASE G2: - Baseline AR&D System
- With plume effect on light target



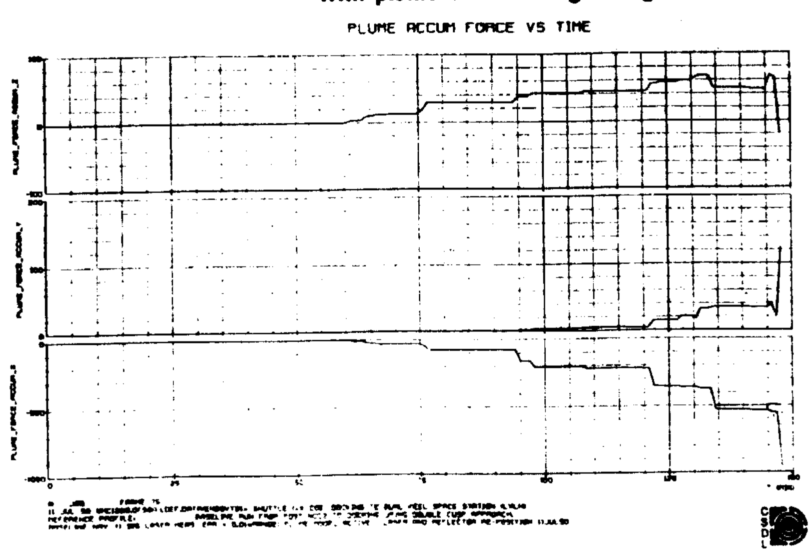
GUIDED VBAR APPROACH (continued)
CASE G2: - Baseline AR&D System
- With plume effect on light target



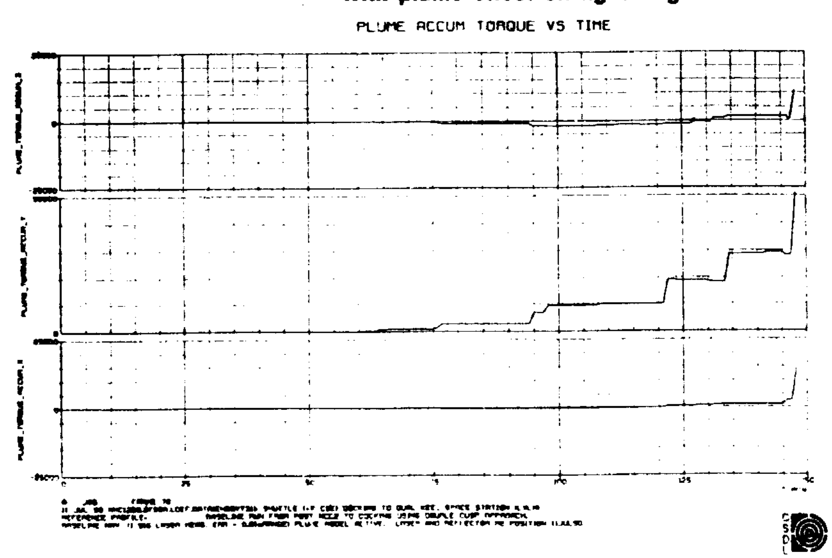
GUIDED VBAR APPROACH (continued)
CASE G2: - Baseline AR&D System
- With plume effect on light target



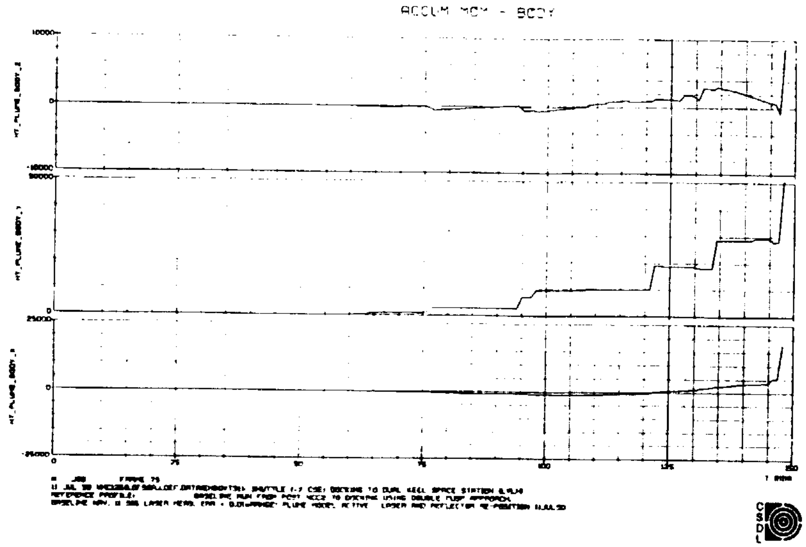
GUIDED VBAR APPROACH (continued)
CASE G2: - Baseline AR&D System
- With plume effect on light target



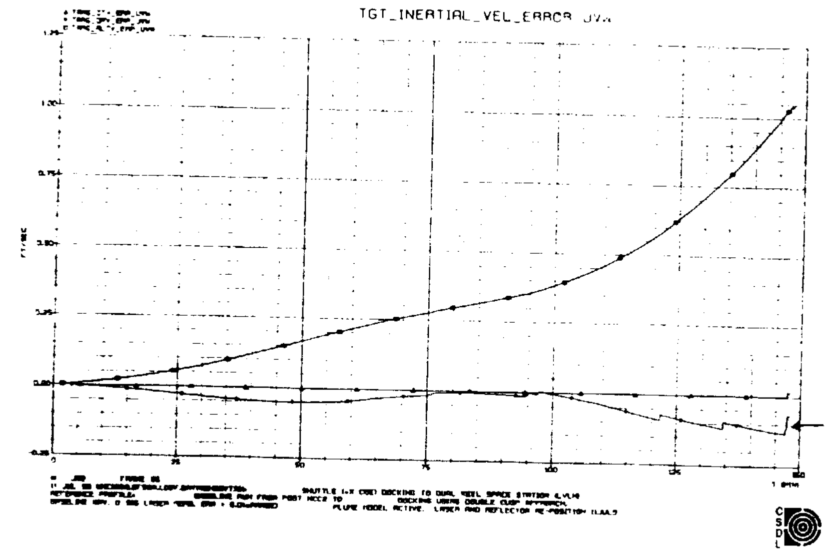
GUIDED VBAR APPROACH (continued)
CASE G2: - Baseline AR&D System
- With plume effect on light target



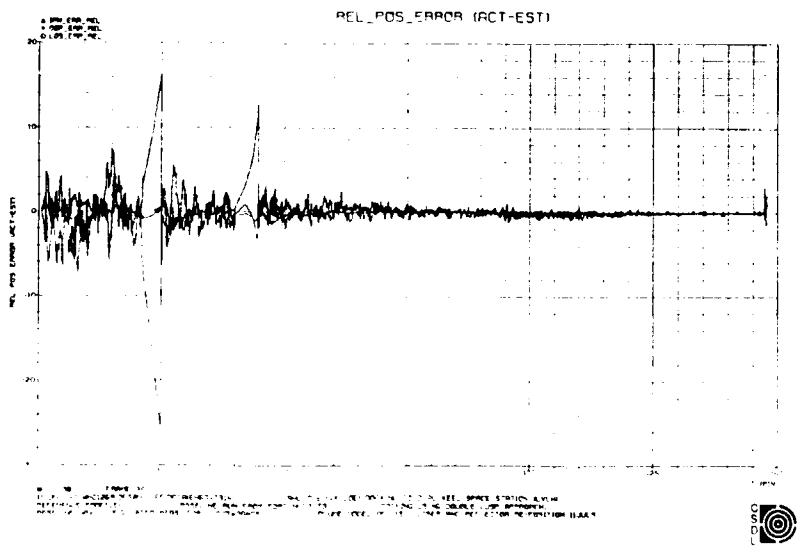
GUIDED VBAR APPROACH (continued)
CASE G2: - Baseline AR&D System
- With plume effect on light target



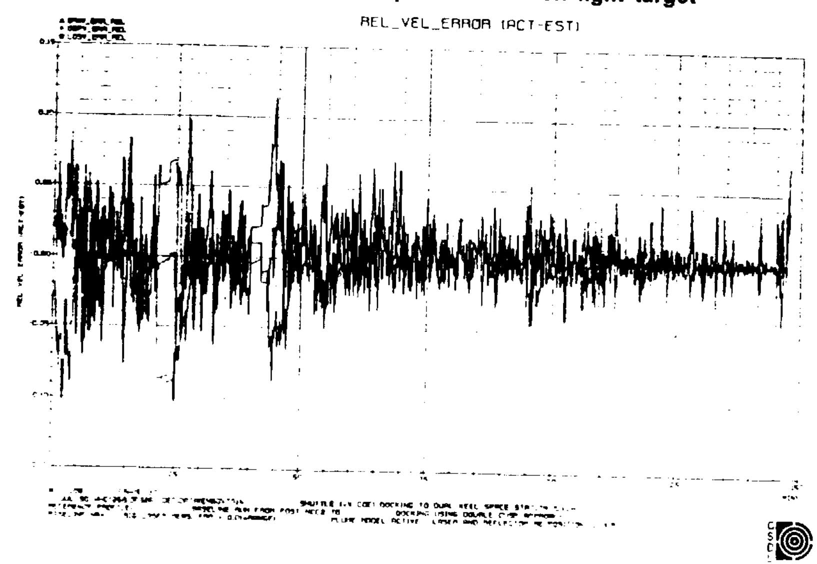
GUIDED VBAR APPROACH (continued)
CASE G2: - Baseline AR&D System
- With plume effect on light target



GUIDED VBAR APPROACH (continued)
CASE G2: - Baseline AR&D System
- With plume effect on light target

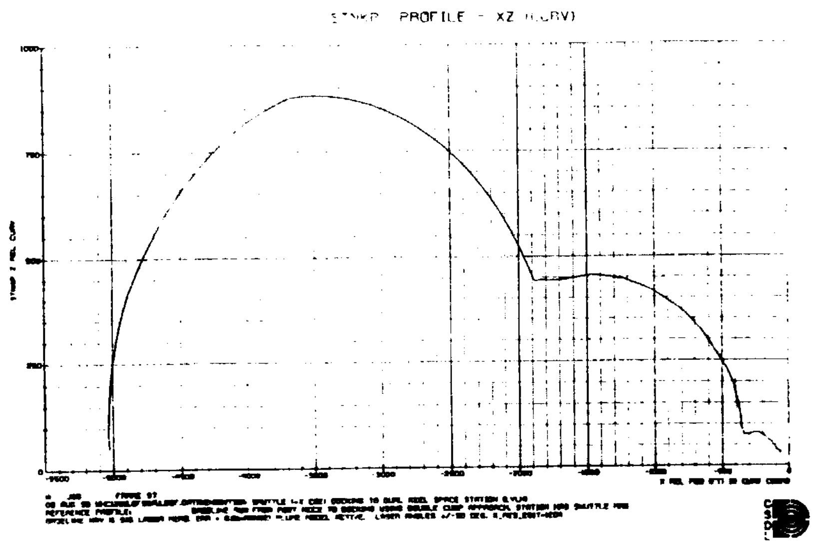


GUIDED VBAR APPROACH (continued)
CASE G2: - Baseline AR&D System
- With plume effect on light target



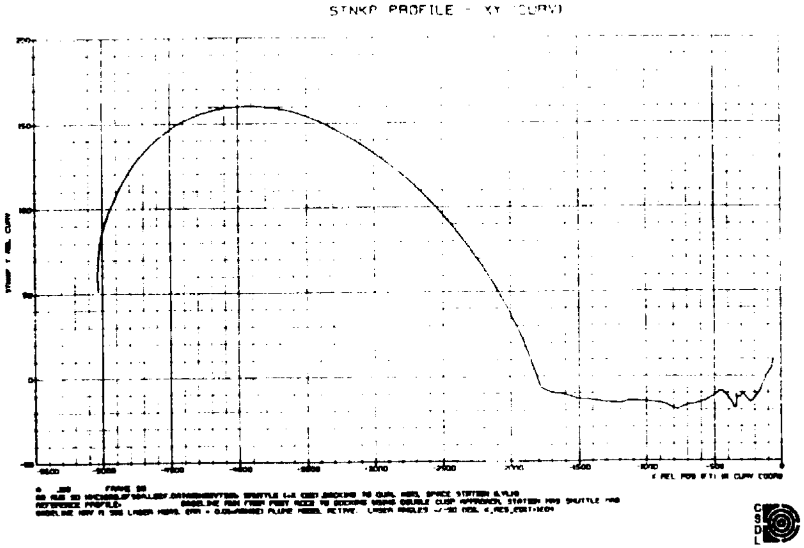
GUIDED VBAR APPROACH

CASE G3: - Baseline AR&D System with Nav filter residual edit change
- With plume effect on light target



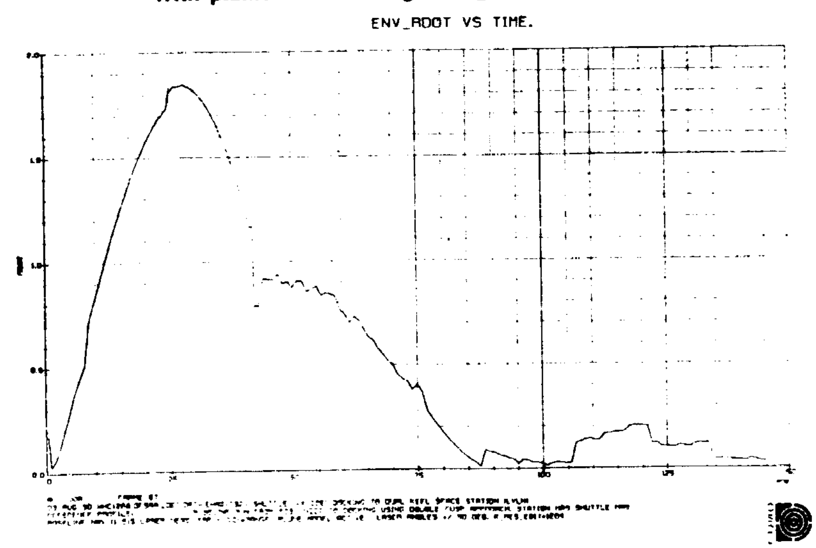
GUIDED VBAR APPROACH (continued)

CASE G3: - Baseline AR&D System with Nav filter residual edit change
- With plume effect on light target



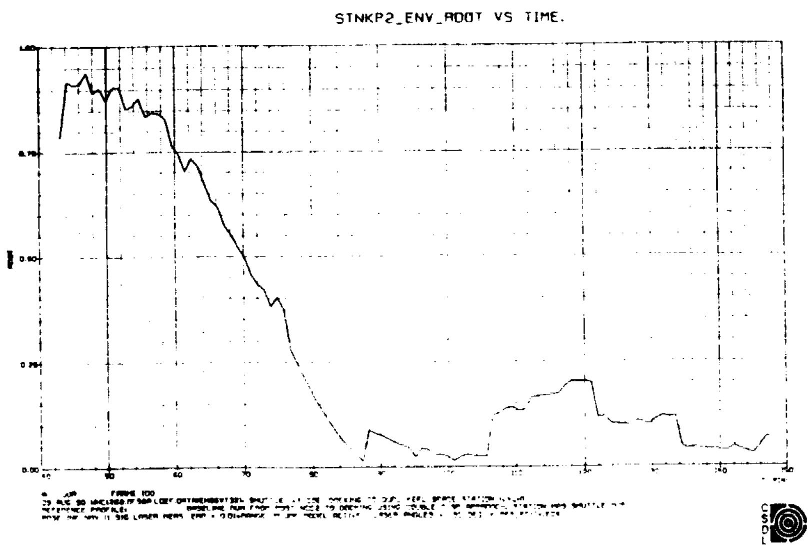
GUIDED VBAR APPROACH (continued)

CASE G3: - Baseline AR&D System with Nav filter residual edit change
- With plume effect on light target



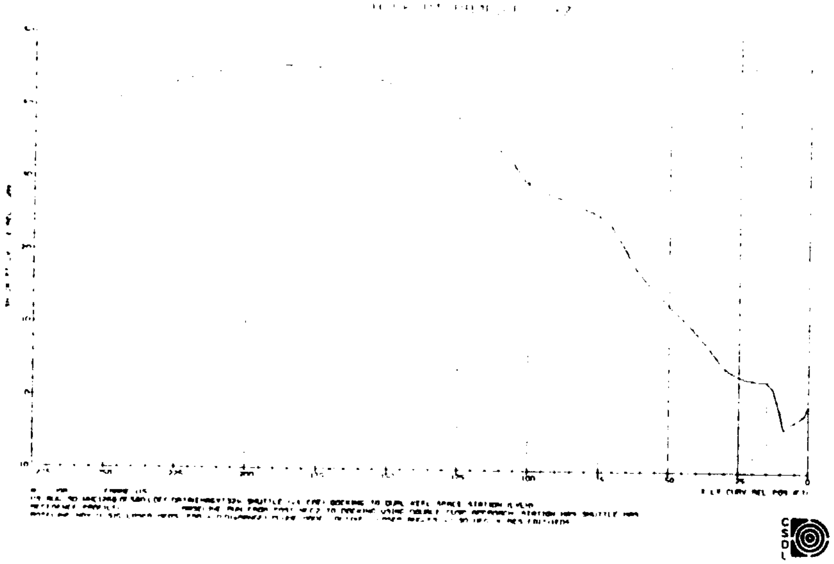
GUIDED VBAR APPROACH (continued)

CASE G3: - Baseline AR&D System with Nav filter residual edit change
- With plume effect on light target



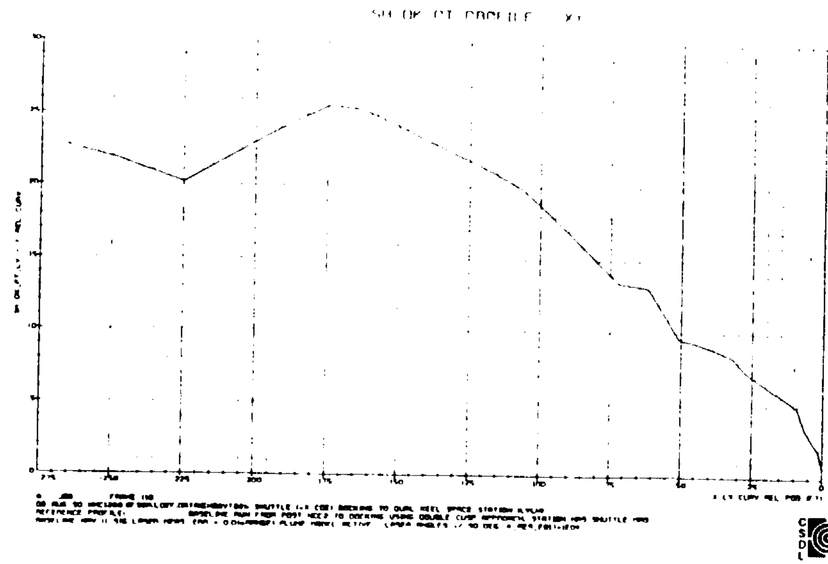
GUIDED VBAR APPROACH (continued)

CASE G3:
- Baseline AR&D System with Nav filter residual edit change
- With plume effect on light target



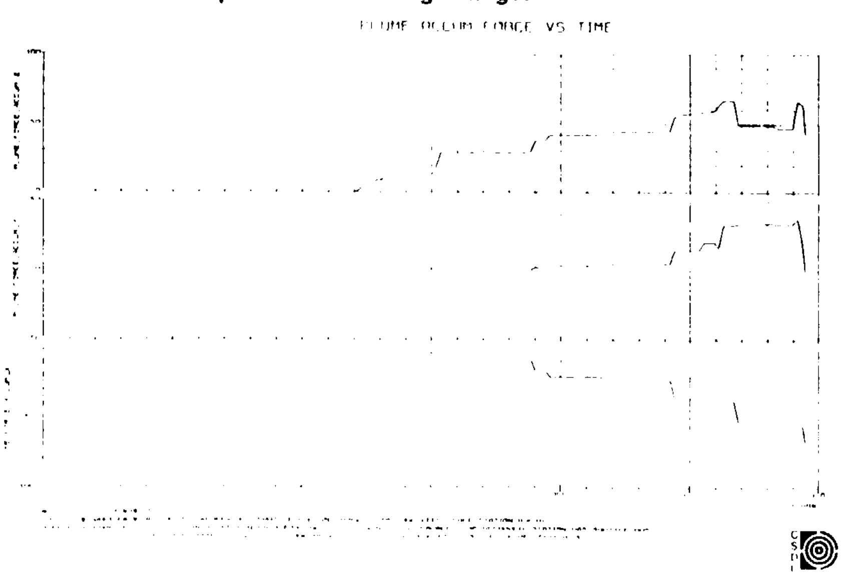
GUIDED VBAR APPROACH (continued)

CASE G3:
- Baseline AR&D System with Nav filter residual edit change
- With plume effect on light target



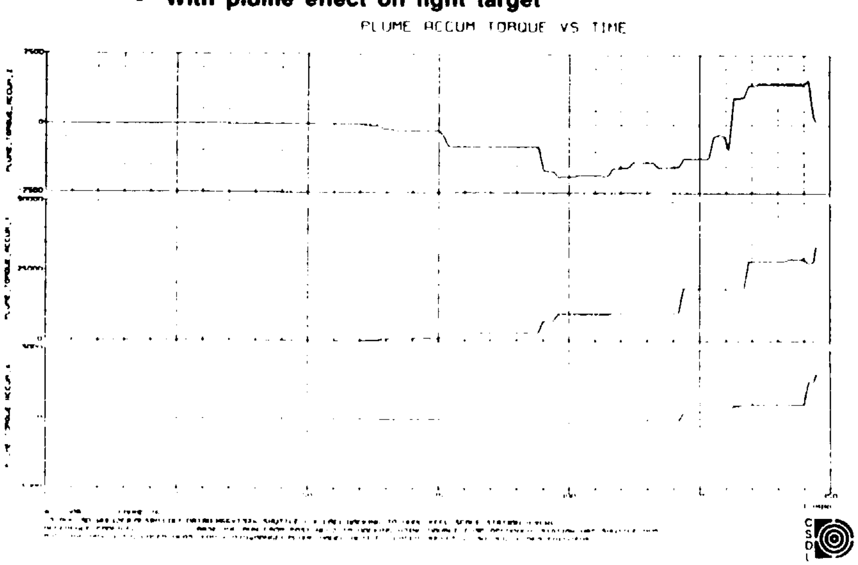
GUIDED VBAR APPROACH (continued)

CASE G3:
- Baseline AR&D System with Nav filter residual edit change
- With plume effect on light target



GUIDED VBAR APPROACH (continued)

CASE G3:
- Baseline AR&D System with Nav filter residual edit change
- With plume effect on light target



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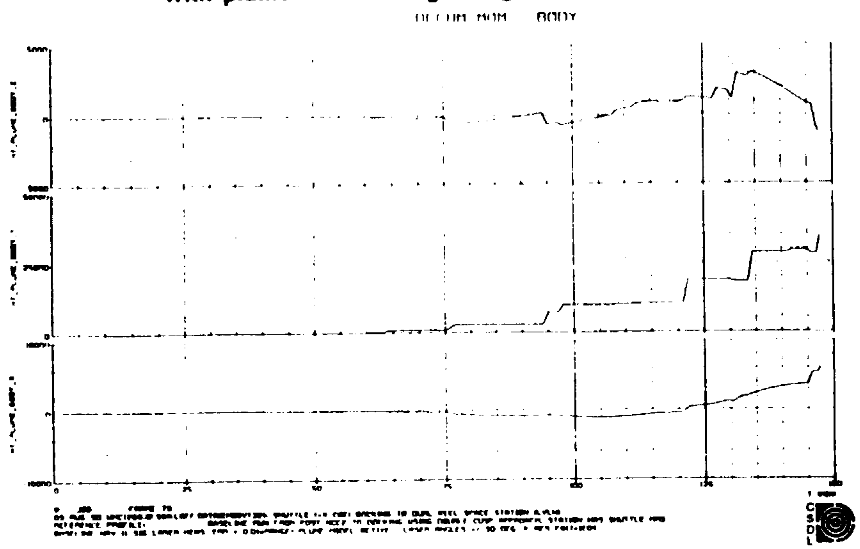
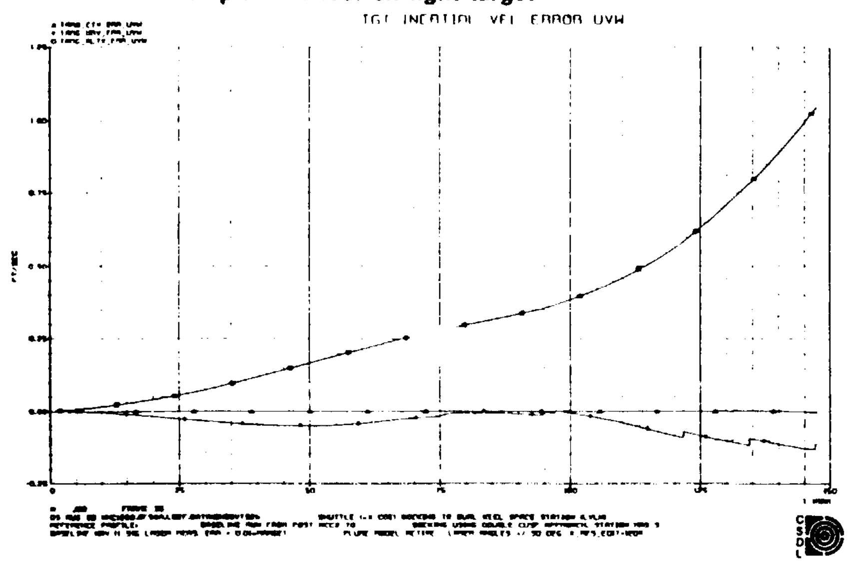
GUIDED VBAR APPROACH (continued)

CASE G3: - Baseline AR&D System with Nav filter residual edit change
- With plume effect on light target



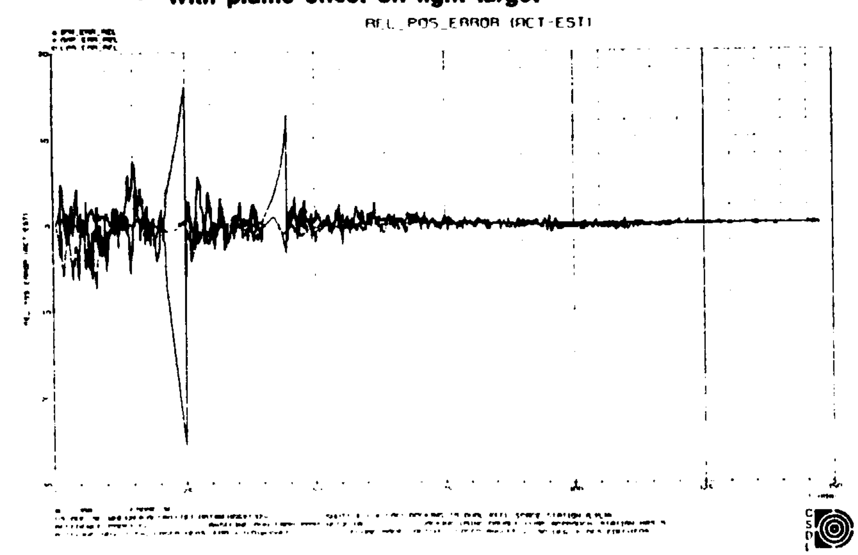
GUIDED VBAR APPROACH (continued)

CASE G3: - Baseline AR&D System with Nav filter residual edit change
- With plume effect on light target



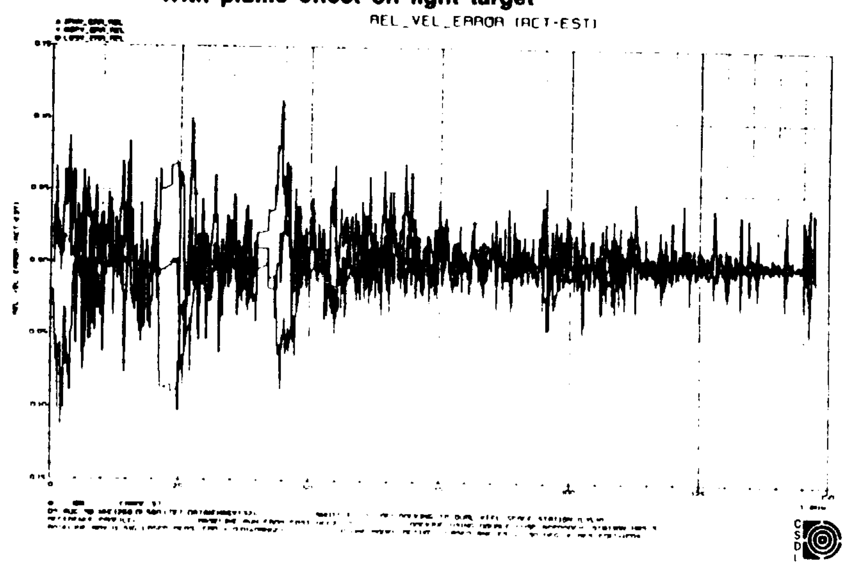
GUIDED VBAR APPROACH (continued)

CASE G3: - Baseline AR&D System with Nav filter residual edit change
- With plume effect on light target



GUIDED VBAR APPROACH (continued)

CASE G3: - Baseline AR&D System with Nav filter residual edit change
- With plume effect on light target



GUIDED VBAR APPROACH

SUMMARY OF RESULTS (cont'd)

TEST CASE	NAV RATE	PLUME YES	TGT WT YES	SUMMARY OF RESULTS
G1	Baseline Laser Nav	X	Heavy	— Overall system performance is good — Docking conditions of 1.0 ft in plane and 0.9 ft out-of-plane at 0.2 fps rate — Final approach to docking port included 10 ft of out-of-plane position travel over the last 10 ft of in-plane travel — Performance can be improved by modifications to the controller to resolve cross-track appears to last 20 ft or so of closure
G2	Baseline Laser Nav	X	Light	— Baseline nav configuration edits marks due to the relative state error growth with plume on the target. Appears as a bad mark on the filter — The state "error" is subsequently estimated but not fast enough for the controller to maintain the approach profile
G3	Baseline with increased residual Edit I-Loads	X	Light	— With nav filter residual edits criteria modified to account for relative error growth, no editing of marks occur — Successful run is achieved but a "stall" condition occurs just before docking port contact — Docking port offsets at this point are 0.7 ft in-plane and 0.8 ft out-of-plane, with a closing rate of -0.0004 fps

GUIDED VBAR APPROACH

SUMMARY OF RESULTS (cont'd)

- Additional results from other simulations
  - — The controller mechanization in the baseline system causes a "stall" condition on some runs
  - — Closure to the port is eventually reestablished, however
  - — Controller mechanization needs to be modified to correct this deficiency, as well as the out-of-plane closure problem discussed above
  - — With these modifications, it is anticipated that system performance will consistently result in acceptable docking conditions for a first phase AR&D system

SUMMARY

- Rendezvous mission phase
  - — Current AR&D system provides acceptable sytem performance
  - — Additional performance analysis for nominal, off-nominal and stress conditions is required, for the various mission designs
  - — Development of a robust Missions Operation Controller is required
- Proximity Operations
  - — Need for an integrated system design approach and high fidelity integrated system performance analysis is evident
  - — Current baseline has problems with both approach controllers as discussed
  - — Modifications to these controllers can be easily made to achieve desired AR&D performance
  - — Additional analysis required for off-nominal and stress conditions
  - — Development of robust Mission Operations Controller to handle contingencies is required

OBSERVATIONS

- Initial guidance, navigation, and control system development must move from a "point design" development mode to an integrated GN&C system development phase at the earliest possible opportunity
- Use of several different "trajectory control" techniques for different programmatic applications can be handled by a generic configuration of the navigation filter with appropriate I-loads modifications
- Guidance/targeting, navigation and control system designs that can accomodate variations in sensor and effector capabilities from spec values are required
  - — This can be achieved by:
    - System or algorithm designs that are capable of handling a variety of conditions through a "conservative" design approach
    - Development of advanced capability "adaptive" systems
- Techniques developed for "manual" system operations, when used for autonomous operations must be augmented to incorporate the judgement and learning functions that human operators acquire through repeated use of the system
- Development and assessment of Phased upgrades in AR&D system capabilities allows determination of resulting performance improvements and provides direction to further development of relevant technologies

A Phased Approach to the Development of an Integrated Guidance, Navigation, and Control System for Autonomous Rendezvous and Docking

Advanced Developments for Proximity Operations

Neil Adams, Edward Bergmann, and Robert Polutchko

C.S. Draper Laboratory, Cambridge, MA 02139

Autonomous Rendezvous and Docking Conference
August 15-16, 1990
Johnson Space Center
Houston, TX

Advanced AR&D System Designs

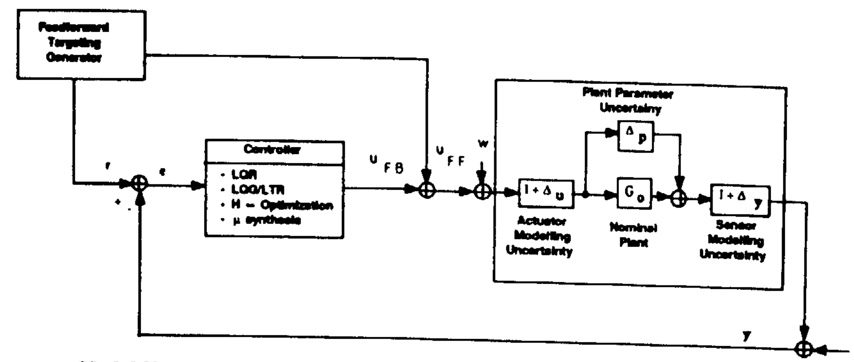
- Robust Control and Estimation - Neil Adams
- Intelligent Planning/Execution Systems - Edward Bergmann
- Cooperative Proximity Operations - Robert Polutchko

Robust Control and Estimation

Robust Control and Estimation

N. Adams

Simplified AR&D System with Modeling Uncertainty



- Model Uncertainties:
  - Mass Properties
  - Orbital Rate
  - Actuator accelerations
  - Actuator or sensor saturations
  - Neglected nonlinearites (bending)

- Disturbances and Noises
  - Gravity gradient and Aerodynamics
  - Plume effects
  - Sensor quantization, noise, and biases

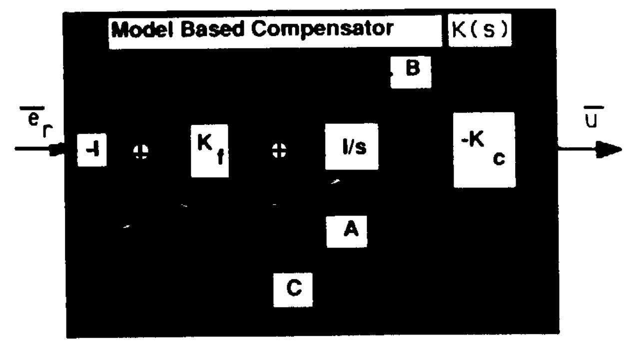
Notes on Application of Robust Control to AR&D

Recent developments in the area of robust control allow determination of compensation for a system design model having modeling uncertainty in various points in the control loop. In addition these techniques allow specification of noise and disturbance spectrums without requiring the models be white noise driven. The approach of these more recent control synthesis techniques has application to the autonomous rendezvous and docking (AR&D) problem since many modeling and parameter uncertainties occur and can be included in the design model. A typical AR&D system may be driven by a prescribed trajectory for which feedback control is required for good tracking and low control effort in the face of modeling uncertainties and spectral noise and disturbance specifications. Neglecting these uncertainties during the design can lead to poor tracking performance, large control effort, or at worst, feedback instability. Use of these robust control techniques will guarantee robust stability for the design model employed.

Several synthesis techniques are possible for the design of robust controllers, each having advantages and disadvantages with regard to practicality of implementation, conservative performance, and type of performance measure. A survey of these considerations will be given. Most of these synthesis techniques develop "model-based compensators" that, for the AR&D problem design what is often termed the "navigation filter", providing state estimates of position and velocity, as well as feedback compensation. Tools for model development, model reduction, and control synthesis are available at C.S. Draper Laboratory for the design of the so-called Linear-Quadratic-Gaussian (LQG) compensators, LQG with loop transfer recovery (LQG/LTR), H_∞ optimization, and μ-synthesis.

CSDL

Model Based Compensators



- LQG/LTR, H_∞ Optimization, and μ-synthesis compensators are all types of MBC's
- MBC State Space:

$$A_{MBC} = A - B K_c - K_f C$$
$$B_{MBC} = K_f$$
$$C_{MBC} = K_c$$

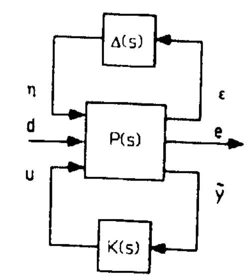
CSDL

Notes on Model-Based Compensators

Model-based compensators include the design model in their compensation as shown in the preceding figure, hence the title of the compensator. These compensators are driven by the error e with respect to the reference trajectory and provide control inputs to keep this error small, while also regulating other states and/or keeping control effort small. Two gain matrices are determined which are then combined to form the overall model-based compensator dynamics. K represents development of state estimates from the measured outputs (i.e., Nav filter) and K represents an "optimal" feedback gain matrix. The optimization is carried out with respect to the performance measure of the synthesis technique being used.

System Modeling

- Modeling errors can be represented by norm-bounded perturbations
- Exogenous inputs represented by d
  - Disturbance forces and torques (process noise)
  - Sensor noise
  - Reference signals
- Performance variables represented by e
  - Tracking errors
  - States to be regulated
  - Actuator effort
- Inputs and outputs are normalized with weighting functions to have unit magnitude at all frequency



Standard 3-Block Representation of Linear Systems

Notes on System Modeling

All linear systems can be place into a standard 3-block structure with norm-bounded modeling uncertainty perturbing the plant. All exogenous signals are combined into one signal d, while components of the desired performance measure are combined in the vector e. Modeling error is generally normalized such that the magnitude or norm of its error is bounded by 1. The "weighting" function W(s) used in the normalization process is then "absorbed" into the plant P(s). Compensation K(s) for the system can then be designed using any of a number of synthesis techniques. System inputs and outputs are generally normalized with frequency weighting functions and scalar weightings so their dynamics are equally accounted for at all frequencies, and so disimilarly dimensioned quantities are viewed with equivalent weights in the optimization.

CSDL

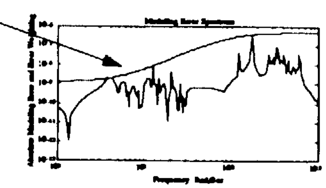
...System Modeling

Norm-Bounded Modeling Errors

$$\longrightarrow \boxed{W(s)} \longrightarrow \boxed{\Delta(s)} \longrightarrow \quad \left| \Delta(s) \right| \le 1$$

- **Unmodeled dynamics**
  - **sensor dynamics**
  - **actuator dynamics**
  - **high-frequency bending modes**

W(s)



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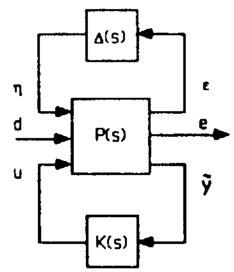
Survey of Robust Control Synthesis Techniques

- **LQR, H_2 (LQG), and LQG/LTR designs:**
  - Minimize 2-norm of error
  - Compensators designed with $\Delta = 0$
  - Modeling error reflected to plant input or output
  - Make robust via bandwidth reductions (if possible) such that:

$$\sigma_{min}\{E(s)\} > \sigma_{max}\{M(s)\} \quad \text{for all } \omega$$

- **H_∞ Optimization designs:**
  - Minimize $\|G\|_\infty$ (G includes Δ)
  - Ignores block diagonal structure of Δ => conservative
- **μ-synthesis designs:**
  - Minimize $\|D^{-1}\,G\,D\|_\infty$ (G includes Δ)
  - Accounts for structure of Δ => less conservative



M = Closed loop system excluding Δ
G = Closed loop system including Δ
E = Modeling uncertainty error dynamics
Δ = Norm-Bounded Modeling uncertainty
D = Unitary Diagonal Scaling Matrix

Notes on Robust Control Survey

Linear Quadratic Regulators (LQR), LQG, and LQG/LTR compensators are all model-based compensators that minimize the 2-norm of the error ("bounded energy") without including modeling uncertainty of the design model. Imposing the robust stability requirement for these techniques requires a conservative reflection of all system modeling error to the plant input or output. The minimum singular value of the error dynamics must then be greater than the maximum singular value of the closed loop system M(s), where M(s) does not include Δ. If this requirment is not met the system bandwidth must be reduced. However, for open-loop unstable plants, it may be difficult to place the poles of the system where desired to meet the robustness criterion.

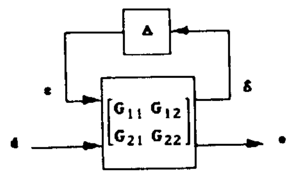
H_∞ optimization minimizes the infinity-norm of the entire closed loop system including Δ. Minimization of the infinity-norm allows the use of the Small Gain Theorem (see notes on Analysis) to determine stability and performance robustness. Application of the small gain theorem to the H_∞ design does not account for the block diagonal structure of the modeling uncertainty due to the independence of the various uncertainties scattered around the system. This leads to a conservative design where achievable performance has been sacrificed to meet the robust stability requirement.

μ-synthesis designs minimize a different infinity-norm (termed μ) that has some extra degrees of freedom prescribed by the unitary matrix D accounting for the block diagonal structure of Δ. An iterative design approach is used that first designs an H_∞ compensator and then minimizes μ over all possible values of D. The new value of D is then used to design a new H_∞ compensator until μ becomes less than 1, which is the robust stability criterion of μ-analysis (see analysis notes).

One disadvantage of both H_∞ and μ-synthesis designs is their increased dimensionality to account for the modeling errors. In some cases, practical implementation may not be possible.

For the AR&D problem, a μ-synthesis design may provide better system performance over a larger range of proximity operations where tracking errors are to be kept small using little control effort.

Robustness Analysis Methods

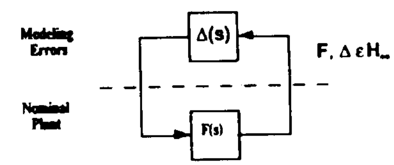


	Stability	Performance
Unstructured (Small Gain Thm)	$\|\|G_{11}\|\|_{H_\infty} < 1$	$\|\|G\|\|_{H_\infty} < 1$
Structured (μ-analysis)	$\|\|G_{11}\|\|_{\mu} < 1$	$\|\|G\|\|_{\mu} < 1$

$$||F||_\mu = \min ||D^{-1} F D||_{H_\infty} < 1 \text{ over } D$$

...Robustness Analysis Methods

- Small Gain Theorem => The system shown below is stable if $||F||_\infty ||\Delta||_\infty < 1$



- Implications for system modeling
  - Order modeling errors so that

    $\Delta(s) = \text{diag}\{\Delta_1(s), \ldots, \Delta_r(s)\}$

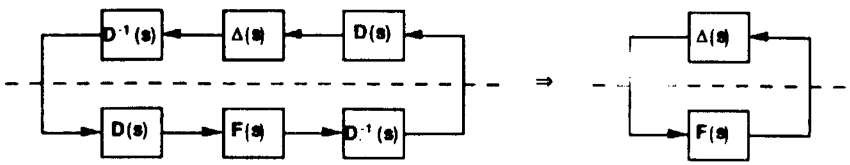
  - Scale so that

    $||\Delta||_{H_\infty} < 1$

  - Allowing arbitrary Δ => conservatism
  - Need to model structure of Δ to remove conservatism => μ-analysis

...Robustness Analysis Methods

- μ-analysis



- Select D so that $D^{-1} \Delta D = \Delta$, where

  $D = \text{diag}(d_1 I_{n_1} \ldots d_k I_{n_k})$

- System stable if there exists a D such that

  $\| D^{-1} F D \|_{H_\infty} < 1$

- Suggests

  $\| F \|_\mu = \min \| D^{-1} F D \|_{H_\infty} < 1$ over D

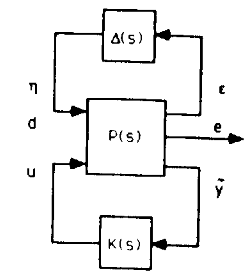
  to assess stability

...Robustness Analysis Methods

- Robust Performance

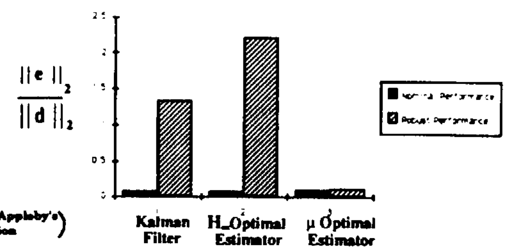
  - Nominal Performance => $\| G_{22} \|_{H_\infty} < 1$
  - Form ficticious performance uncertainty Δ_p
  - Scale plant by maximum allowable outputs
  - $\| \Delta_p \|_{H_\infty} < 1$
  - Performance requirement satisfied for all structured Δ iff

    $\| G \|_\mu < 1$



Robust Estimation

- Example Problem ==> Second-order plant with:
  - Real parameter error in modal frequency
  - Unmodeled high frequency bending modes
- Shaping filter to represent process noise spectrum
- μ estimator is insensitive to modeling error



(Excerpts from Brent Appleby's Phd. dissertation)

Notes on Robust Estimation

Reference: Appleby, B, Phd Dissertation in progress, MIT, December 1990.

Design of estimators without the incorporation of modeling uncertainty in the design model can also lead to degraded performance and higher estimation error. Kalman filter design assumes all process and measurement noises are white noise driven. In addition, Kalman filter synthesis does not include a method for incorporating performance robustness to modeling uncertainties during the actual design process. Simulation is the often used method for determining satisfactory performance. In short, Kalman filters do not provide the "optimal" estimation gain matrix when modeling uncertainties are present. The actual design model may have elements of the linear state space corrupted by perturbations from nonlinearites are other model approximations. Through duality, H_∞ optimal estimators and μ optimal estimators can be designed. The same caveats exist as for robust control with respect to incorporation of modeling uncertainty and its' implicit block diagonal structure. It is possible, as shown in the preceding bar chart, to derive a μ optimal estimator that has nearly the same robust performance (i.e., performance that accounts for known modeling uncertainties) as the Kalman filter has nominal performance (i.e., performance achieved with no model uncertainty). Notice the significant increase in Kalman filter estimation error when known modeling uncertainty is allowed to perturb the Kalman filter design. The H_∞ design does not account for the block diagonal structure of the plant and so may provide a more conservative design which sacrifices achievable performance. Its design advantages with respect to Kalman filter theory will therfore depend on the system model being used.

... Robust Estimation

- **Stability**
  - Closed-loop stable for all structured D iff

    $\|G_{11}\|_\mu < 1$

  - G_{11} is independent of estimator design

- **Performance**
  - Normalized performance requirement

    $$\frac{\|e_2\|}{\|d_2\|} < 1$$

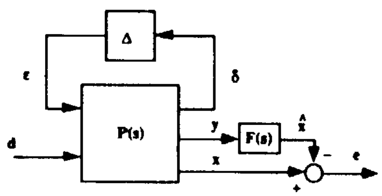
    is satisfied for all structured D iff

    $\|G\|_\mu < 1$

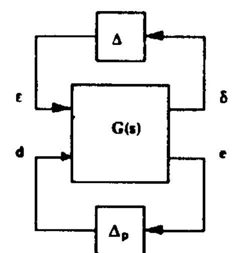
- **m computed via**

  $\|F\|_\mu = \min \|D^{-1} F D\|_{H_\infty} < 1$ over D

Design Model



Analysis Model



(Excerpts from Brent Appleby's Phd. dissertation)

Design Tools for Robust Control and Estimation

- **Complete software support for robust control and estimation synthesis exists at CSDL**
  - MATLAB on DecStation 3100 and on Macintosh IIx's
  - Model building software:
    - Input/Output frequency setup and frequency weighting
    - Model Reduction
    - Dynamical and parameter model uncertainty incorporation
  - Robust control synthesis methodologies implemented:
    - LQG/LTR
    - H_∞ Optimization
    - m-synthesis
  - Robust estimator synthesis methodologies implemented:
    - Minimax
    - H_∞ Optimal
    - m-synthesis
  - Analysis including small gain and m-analysis techniques

Intelligent Planning and Execution System

Intelligent Planning and Execution System

E. Bergmann

CSDL

Intelligent Planner/Execution System

Problem

Proximity operations may require real-time rapid replanning
- **collision avoidance**
- **plume impingement avoidance**
- **failures**

Proximity operations may require high level of precision and reliability
- **limits on closing, contact velocity as well as relative attitude and position**
- **multi-point docking systems**
- **crew return**

Contingencies may require non-obvious solutions

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Intelligent Planner/Execution System

Problem notes

Collision avoidance may entail other moving targets or components of the chase or target vehicle such as wings, solar arrays, etc

Impingement of jet plume on target may be constrained for dynamic or scientific reasons. The jets to be deselected may change as the operation evolves and different jets face the target. The intent is to deselect only those jets which plume the target, and reselect those jets as they point away from the target, maximizing the available control authority at each point

Jet failures may occur during the operation. Rather than abort, the planner evaluates the requirement for the failed jet. If it is not required, the system proceeds with the original plan. If it is used, the system develops a new plan which works around the jet failures.

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Intelligent Planner/Execution System

Problem notes

Certain proximity operations may require precise docking conditions to avoid unduly exciting the structure or because of a small envelope at the docking port. Crew rescue may require a high degree of reliability and time criticality.

Multi point docking systems require simultaneous contact with several fixtures, imposing strict limits on relative attitude and position. Relative rates are also critical to avoid "bouncing" off the target before latching.

In some cases, few obvious solutions to the constraints may be available. In a contingency situation, the best solution may be non-intuitive. A planner such as that described here may develop several options for a given situation which may not otherwise appear.

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Intelligent Planner/Execution System

Design Concept

Apply intelligent planning techniques to proximity operations

- Heuristic optimal searches over 6DOF state space and effectors for coherent optimal trajectory, attitude, and control
- Couple system with jet FDI, collision detection, and dynamic plume detection to meet constraints
- System can operate as:
  - Pilot associate
  - Mission preplanning
  - Fully autonomous prox ops system
- System contains elements of guidance and control rather than interfacing point designs

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Intelligent Planner/Execution System

Concept notes

Intelligent planners have been developed as pilot associates for certain tactical missions, maximizing mission reliability and payoff while dealing with threats, failures and limitations arising during the mission. This system is a direct analog of that proven concept.

Two search techniques have been explored: A* search which is a tree search technique and a gradient optimization method.

The system currently accomodates inputs describing obstacle motion, jet failures and plume impingement, and uses this information in planning. By including jet failure detection, plume impingement prediction, and collision prediction logic into the system, the system has more freedom to explore alternatives, and gains an autonomous capability to react to problems as they arise.

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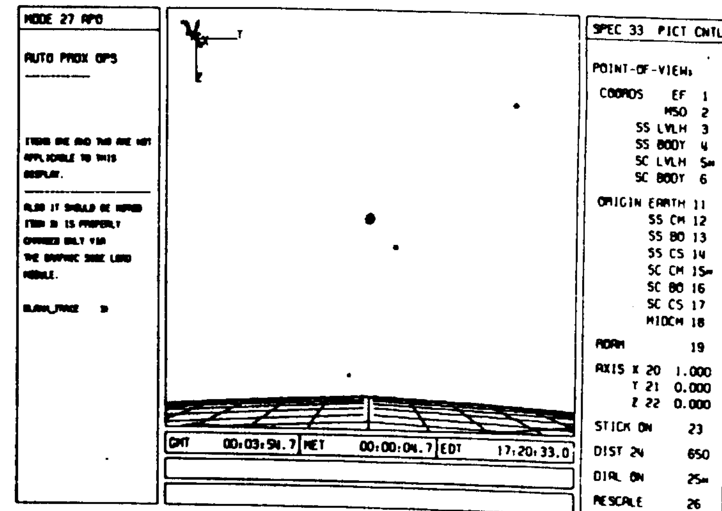
Intelligent Planner/Execution System

Concept notes

This system was originally conceived as an autonomous system capable of planning and executing proximity operations subject to complicated constraints. This system can also be used as a planning aid, by developing and evaluating options as part of the mission planning process. Development of a crew interface would allow use of this tool as a pilot associate, where the system develops alternate plans and presents them to a human pilot for implementation and monitoring.

This system encompasses parts of both the traditional guidance and control functions. By so doing, trajectories are planned considering the available control capability, rather than based on an ideal model of the vehicle and control. Tests suggest a significant benefit in both performance and failure response is obtained by performing the guidance and control functions in this highly integrated fashion.

Intelligent Planner/Execution System



Intelligent Planner/Execution System

Example notes

The slides show snapshots in time of a rendezvous of the shuttle with the Hubble Space Telescope (HST). All views are centered on HST. The first slide shows the shuttle, a target vehicle HST (marked x), and four obstacles. The obstacle closest to the HST is formationkeeping with HST while the obstacle closest to shuttle is formationkeeping with the shuttle prior to its maneuver. The other two obstacles are moving in their own orbits (represented by CW equations in planner) and are moving toward the HST passing in the path of the maneuvering shuttle. The initial shuttle attitude is -ZLV, +X into the velocity vector. The final attitude is constrained to +Z into the velocity vector and +X along the orbit angular momentum vector.

Subsequent slides show the shuttle slowing to maneuver around an obstacle then turning back toward HST to avoid the second moving (relative to HST) obstacle. A small maneuver is also required to avoid the obstacle formationkeeping with the HST. A closing velocity constraint of 0.05 ft/sec is imposed during the terminal phase of the maneuver to be followed by formationkeeping of the two vehicles with a tolerance of 5 ft.

Obstacles are spheres 10 ft in diameter. Planning algorithm requires 100 ft cg to cg miss distance between shuttle and obstacles for collision avoidance.

Fuel consumed to complete rendezvous *without* collision avoidance planning was 175 lbs. Fuel consumed *with* collision avoidance planning was 195 lbs using the gradient optimization algorithm. The rendezvous profile took 5700 seconds to complete.

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Intelligent Planner/Execution System

Example notes

I.C.'s in HST centered LVLH coordintes are:

	X	Y	Z
Shuttle Position	1000	-1000	1000
Stationary obstacle #1 Position	890	-1030	-1040
Stationary obstacle #2 Position	-20	100	100
Moving obstacle #1 Position	-200	500	-400
Moving obstacle #2 Position	600	-100	750

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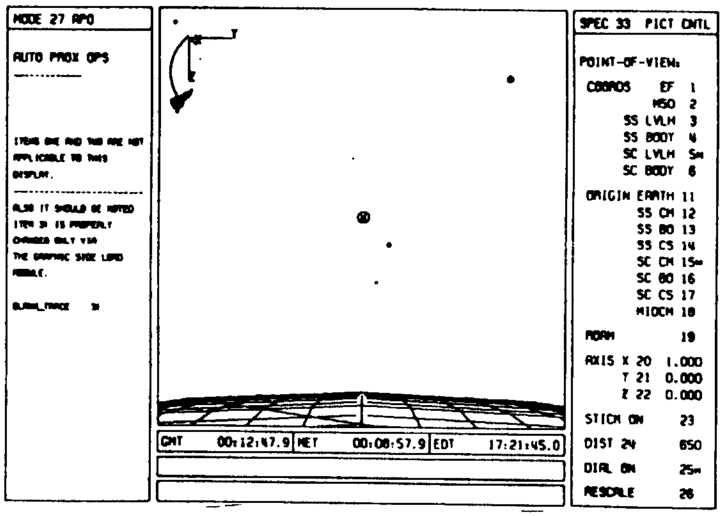
Intelligent Planner/Execution System



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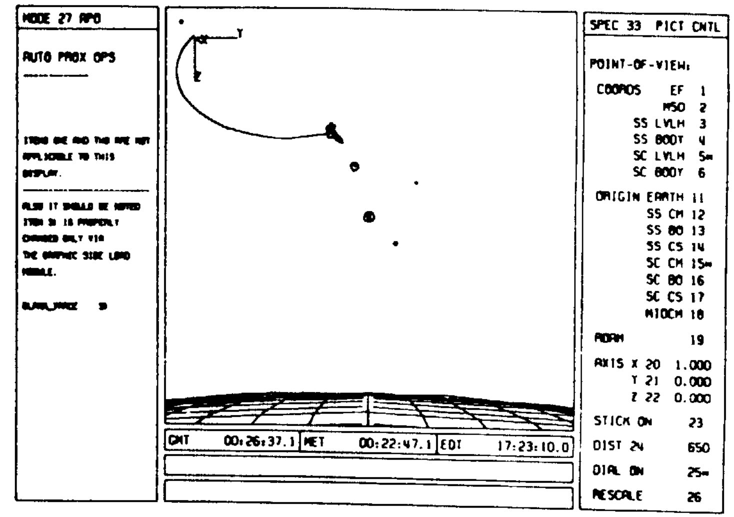

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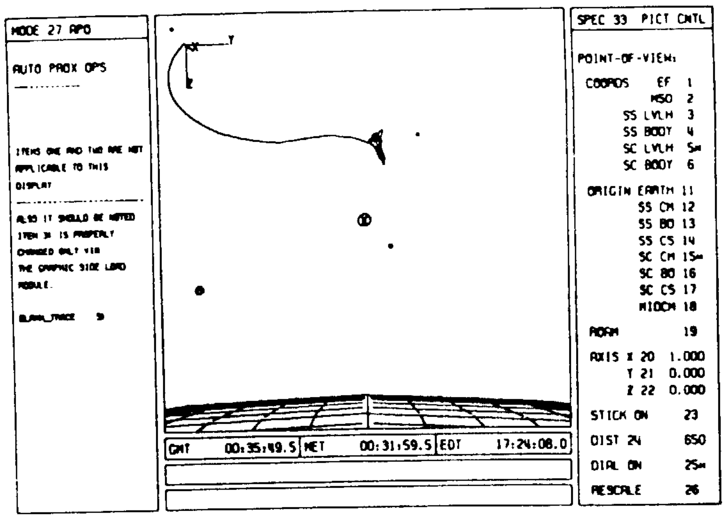
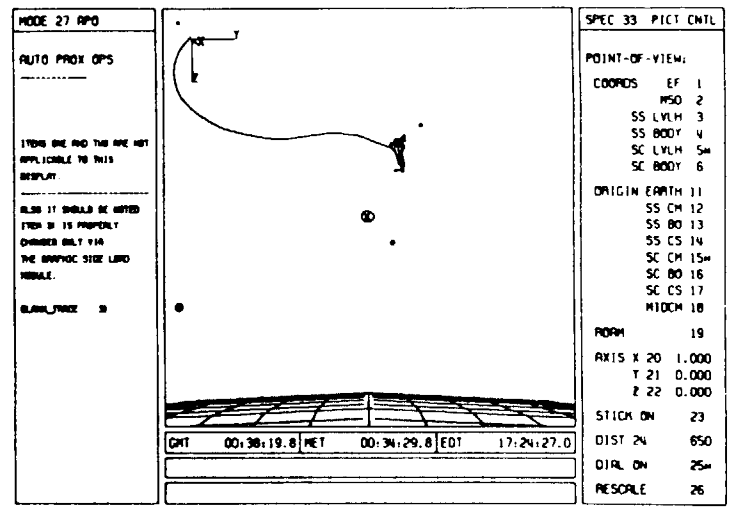
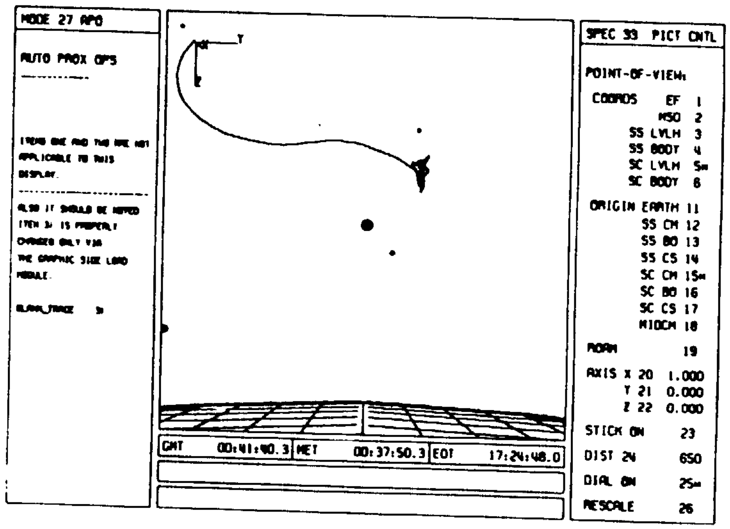


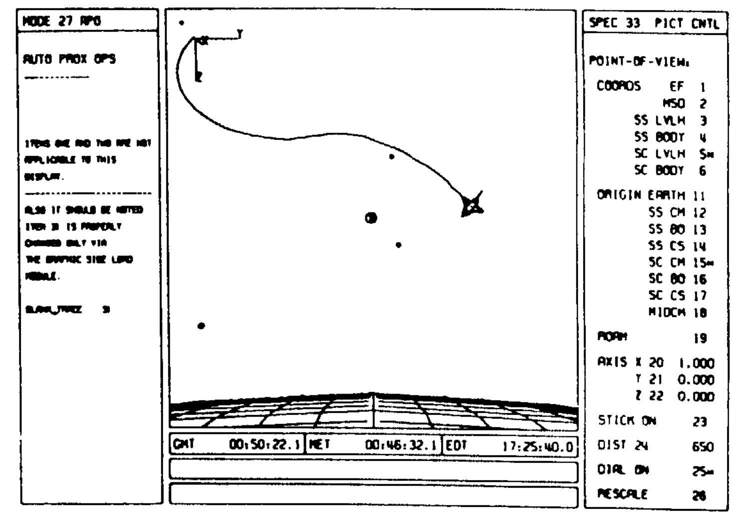
Intelligent Planner/Execution System



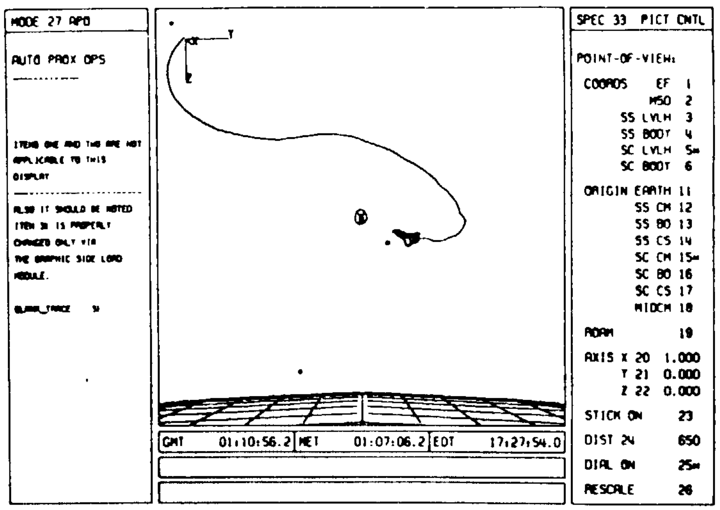
Intelligent Planner/Execution System



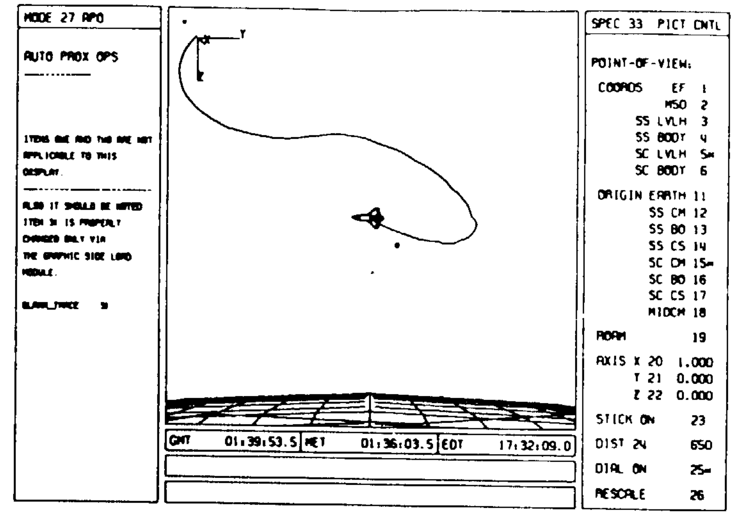
Intelligent Planner/Execution System



Intelligent Planner/Execution System



Intelligent Planner/Execution System



Intelligent Planner/Execution System

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Cooperative Proximity Operations

Cooperative Proximity Operations

R. Polutchko

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Motivation for a Cooperative Approach

"TRADITIONAL" APPROACH TO PROXIMITY OPERATIONS -

- PASSIVE TARGET VEHICLE
- ACTIVELY MANEUVERING "CHASE" VEHICLE
- EXAMPLE: HST / SHUTTLE

FUTURE -

- TARGET VEHICLE WILL ALSO POSSESS CAPABILITY TO MANEUVER
- EXAMPLES: OMV FOLLOW ON, MRSR RENDEZVOUS VEHICLES

OBSERVATION -

IT IS "WASTEFUL" TO ARBITRARILY CONSTRAIN AN AGILE VEHICLE TO REMAIN PASSIVE.

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The Cooperative Approach

PROBLEM: TO SAFELY AND EFFICENTLY COORDINATE THE ROTATIONAL & TRANSLATIONAL MANEUVERS OF TWO COMPLEX SPACECRAFT

SOLUTION: - CONSIDER THE TWO VEHICLES AS A SINGLE SYSTEM

- ACTUATOR SUITE IS SUM OF THE INDIVIDUAL SETS OF JETS, CMGS, ETC.
- THE SYSTEM HAS 12 DEGREES OF FREEDOM (6 TRANSLATIONAL, 6 ROTATIONAL)

- DESIGN A SINGLE INTEGRATED GUIDANCE AND CONTROL SYSTEM TO SIMULTANEOUSLY COORDINATE ALL TRANSLATIONAL AND ROTATIONAL MANEUVERS.

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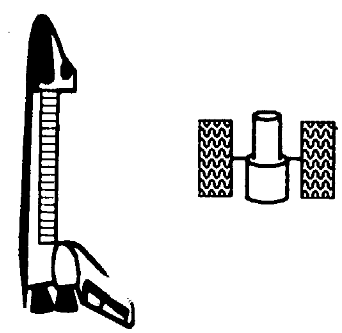
Comparison of Prox Ops Approaches

"TRADITIONAL" PROXIMITY OPERATIONS:

ACTIVE CHASER / PASSIVE TARGET



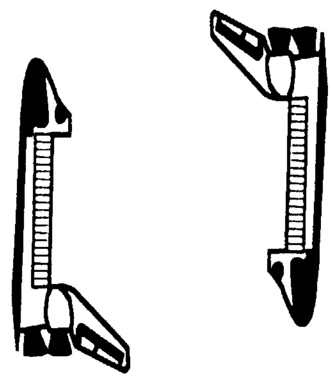
STATES CONTROLLED: RELATIVE ATTITUDE
RELATIVE POSITION

ACTUATORS EMPLOYED: CHASE VEHICLE ACTUATORS ONLY

MANEUVERS: PERFORMED BY CHASE VEHICLE

COOPERATIVE PROXIMITY OPERATIONS:

TWO ACTIVELY CONTROLLED SPACECRAFT



STATES CONTROLLED: RELATIVE ATTITUDE
RELATIVE POSITION
"ABSOLUTE ATTITUDE" OF ONE VEHICLE

ACTUATORS EMPLOYED: ALL ACTUATORS ON BOTH VEHICLES

MANEUVERS: PERFORMED BY THE MASTER, THE SLAVE OR MOST OFTEN BY BOTH

Prox Ops Approach Comparison Notes

- The "traditional" approach to proximity operations controls the translation and rotation of the chase spacecraft in order to achieve a prescribed relative state and relative attitude. The space shuttle controls rotation and translation separately.

- The cooperative approach simultaneously controls the relative attitude, the relative position, and the attitude of the master with respect to an external coordinate frame using all the available actuators on both vehicles.

- Though applicable to any two spacecraft, the cooperative proximity operations system was developed using a shuttle orbiter for both the master and the slave vehicle.
  - Shuttle's asymmetrical mass distribution and complicated configuration of forty-four reaction control jets make it a fine example of a general class of complex, maneuverable sp
  - Two identical spacecraft are employed to ensure that the difference in performance between the standard single vehicle control architecture and the new cooperative control architecture is not a consequence of introducing a more efficient or otherwise superior spacecraft in place of the non-maneuvering target vehicle. Specifically, the use of two shuttle vehicles facilitates direct comparisons between the cooperative approach and traditional "shuttle as a pursuit vehicle" proximity operations solutions.

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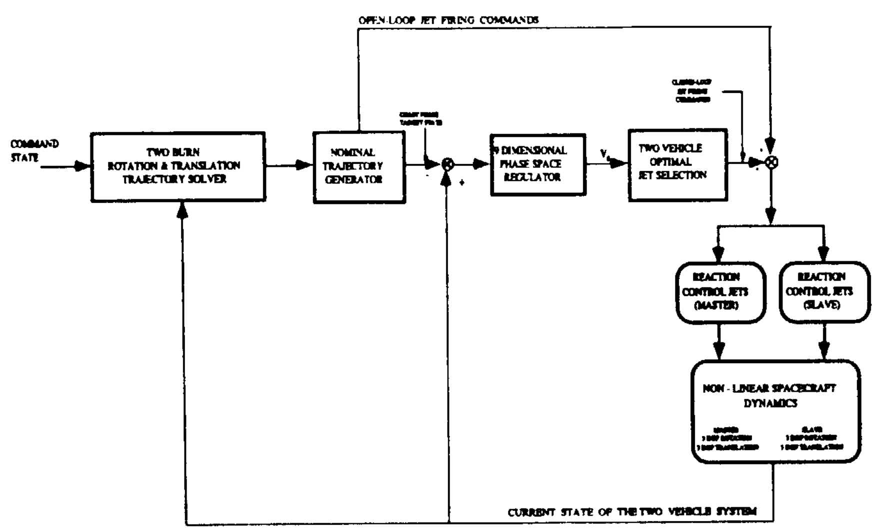
Cooperative System Architecture

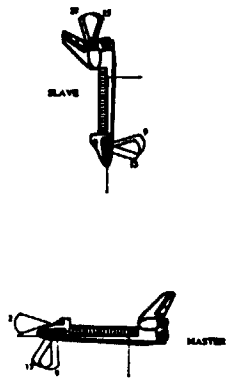


Cooperative System Architecture Notes

- The outer-loop of the cooperative G&C system computes a set of acceleration jet firings, a nominal coast trajectory, and a set of deceleration jet firings which transition the two vehicle system from the current state to the commanded state.
  - Relative translation is targeted using a Clohessey-Wiltshire formulation.
  - Relative rotation and rotation of the master vehicle w.r.t. an external frame is targeted using an eigen axis rotation formulation.
  - The Feed-Forward acceleration and the deceleration jet firing commands are computed for both spacecraft using a Simplex algorithm to minimize fuel usage.
- The inner-loop of the cooperative G&C system computes feedback jet firings which compensate for disturbances and system non-linearities in order to maintain the system within a specified deadband about the nominal 9 dimensional trajectory.
  - If the deadband is exceeded the Phase Space regulator provides a 9 dimensional velocity-to-be-gained vector to the Simplex Jet Select algorithm.
  - The Simplex Jet Select assigns "on" times to a subset of the available actuators on both vehicles in order to satisfy the velocity-to-be-gained request and minimize fuel usage.

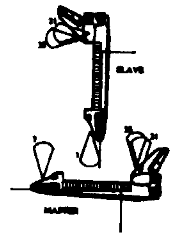
Cooperative Proximity Operations

All jets available



Master		Slave	
Jet #	Time	Jet #	Time
2	2.00	27	3.92
9	0.16	15	3.84
13	0.16	9	0.16
29	0.0	13	0.16
43	0.0		

Acceleration jet firings



Master		Slave	
Jet #	Time	Jet #	Time
21	1.12	1	3.84
33	1.12	33	0.64
7	1.04	21	0.56
17	0.0	11	0.08
		29	0.0

Deceleration jet firings.

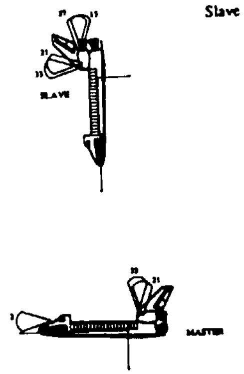
Example Notes

"R BAR" CLOSURE MANEUVER: ALL JETS AVAILABLE

- The vehicles are commanded to decrease the distance between their centers of mass while maintaining their relative attitude and the attitude of the master w.r.t. the Local Vertical / Local Horizontal (LVLH) coordinate frame. Though the Simplex jet selection algorithm optimizes jet usage by simultaneously considering both the force and the torque provided by each jet, in this example the principle effect of each firing is easily discernable.
- Acceleration Firings (left side):
  - SLAVE: Initiates the closure with aft RCS firings. Short forward RCS firings for attitude maintenance.
  - MASTER: Forward RCS are used for lateral translation control; (master is in a lower orbit). Short forward/down RCS firings are used for attitude maintenance.
- Deceleration Firings (right side):
  - SLAVE: Partial cancelation of the closure velocity is performed using a forward jet firing. Aft RCS jet firings are employed for attitude maintenance.
  - MASTER: Upward RCS firings complement the slave firing to cancel the closure velocity.
- Note the plume effect from jet #1 on the slave vehicle. It may be desirable to deselect this jet. (See the next example).

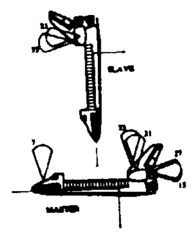
Cooperative Proximity Operations

Slave forward and master +Z jets unavailable



Master		Slave	
Jet #	Time	Jet #	Time
2	2.88	27	4.48
33	0.32	15	4.40
21	0.32	21	.24
43	0.08	33	.24
4	0.0		

Acceleration jet firings.



Master		Slave	
Jet #	Time	Jet #	Time
33	2.40	21	0.16
7	2.32	33	0.16
21	2.32	29	0.00
27	0.80		
15	0.72		

Deceleration jet firings.

Example Notes

"R BAR" CLOSURE MANEUVER: SLAVE FORWARD & MASTER +Z JETS UNAVAILABLE

- Acceleration Firings (left side):
  - SLAVE: Initiates the closure with aft RCS firings
    Short aft/upward RCS firings are employed for attitude maintenance.
    (Slave forward jets unavailable)
  - MASTER: Forward RCS are used for lateral translation control; (master is in a lower orbit)
    Short aft/upward RCS firings for attitude maintenance.
    (Master downward jets unavailable)
- Deceleration Firings (right side):
  - SLAVE: Aft RCS firings for attitude maintenance
  - MASTER: Increased firing times on upward RCS firings to cancel the closure velocity
- NOTE: If the master spacecraft had been a passive target, the slave spacecraft could not have decelerated to complete the maneuver. By exploiting the available actuators on the traditionally passive vehicle the cooperative proximity operations system was able to safely complete the "R Bar" approach.

Benefits of Cooperative Proximity Operations

- ADAPTABLE IN REAL-TIME TO ACTUATOR UNAVAILABILITIES
- REDUCES TO AN ADVANCED SINGLE VEHICLE G&C SYSTEM WHEN EITHER VEHICLE IS CONSTRAINED TO BE PASSIVE.
- RECONFIGURABLE TO OPERATE IN 3, 6, OR ALL 12 DEGREES OF FREEDOM OF THE TWO VEHICLE SYSTEM.
- MAY BE HOSTED ON EITHER SPACECRAFT (OR BOTH FOR COMPUTATIONAL REDUNDANCY)

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Summary

- Three advanced topics for AR&D system designs have been presented
  - Robust Control and Estimation
  - Intelligent Planning and Execution
  - Cooperative Proximity Operations

- All three topics provide integrated designs at some level avoiding integration of separate point designs.
- Each of the designs provides some of the following: increased flexibility, improved performance and robust stability, crew augmentation, and better mission planning capability.

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MISSION OPERATIONS DIRECTORATE

SHUTTLE

RES GESTA PER EXCELLENTIAM

MISSION OPERATIONS

FREEDOM

SPACECRAFT RENDEZVOUS PERFORMANCE REQUIREMENTS REVIEW

AUGUST 15-16, 1990

DON J. PEARSON

SPACECRAFT RENDEZVOUS PERFORMANCE REQUIREMENTS REVIEW

* AUTO RNDZ INVOLVES TRAJECTORY CONTROL FROM LAUNCH THROUGH DOCKING.

  * RENDEZVOUS REGIMES:

    ** LAUNCH PHASE
    ** ORBIT ADJUST PHASE
    ** RELATIVE NAVIGATION PHASE
    ** PROXIMITY OPERATIONS PHASE
    ** DOCKING PHASE

  * PERFORMANCE REQTS FOR EACH PHASE DEPEND ON

    ** HANDOFF CONDITIONS FROM PREVIOUS PHASE
    ** HANDOFF REQUIREMENTS FOR NEXT PHASE

RENDEZVOUS FLIGHT PHASES : CHARACTERISTICS

1. LAUNCH PHASE : USES TGT STATE VECTOR KNOWLEDGE TO COMPUTE

    * LAUNCH WINDOW

    * INSERTION TARGETS

        ** FUNCTION OF LAUNCH TIME IN WINDOW

        ** YAW STEERING TO PHANTOM PLANE (REGRESSES TO TGT AT RETRIEVAL)

CONTROL DISPERSIONS THROUGH EXTENDED POWERED FLIGHT

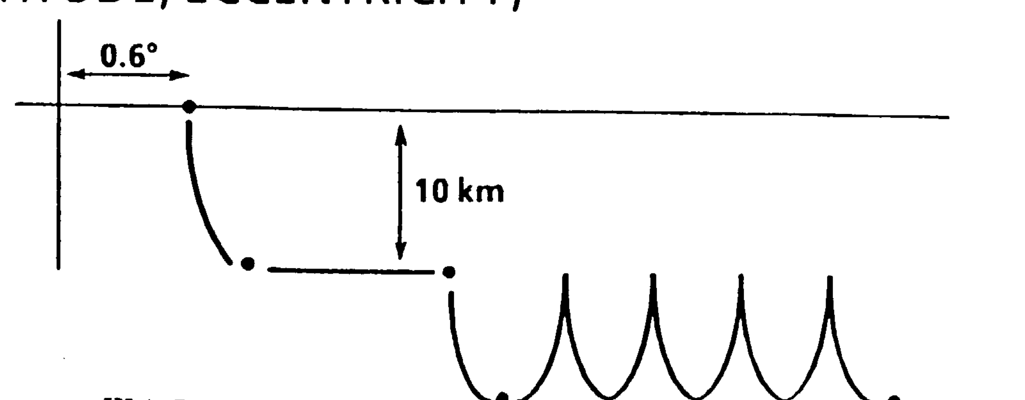
RENDEZVOUS FLIGHT PHASES : CHARACTERISTICS

2. ORBITAL ADJUST FLIGHT PHASE : ONORBIT MANEUVERING BASED ON INERTIAL NAV SYSTEMS

* RANGES TOO LARGE FOR VEHICLE TO VEHICLE TRACKING
    ** R > > 100 KM

* EACH VEHICLE TRACKED SEPARATELY
    ** SUPPORT FROM ABOVE (eg GPS, TDRSS)
    ** SUPPORT FROM BELOW (eg TACAN, GSTDN)
    ** SUPPORT FROM FAR AWAY (eg DSN FOR LUNAR AND MARS ORBITAL OPERATIONS

* MANEUVERS CONTROL PHASE, ALTITUDE, ECCENTRICITY, PLANE AND OCCUR INFREQUENTLY (REVS APART)



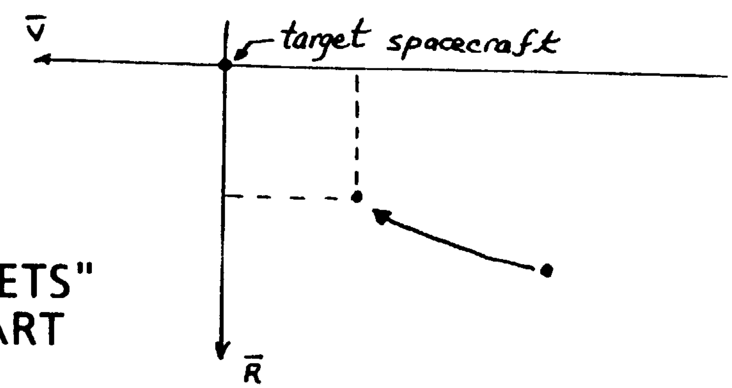
RENDEZVOUS FLIGHT PHASES : CHARACTERISTICS

3. RELATIVE NAVIGATION FLIGHT PHASE : DIRECT ONBOARD SENSING OF TARGET VEHICLE

* RANGES TYPICALLY LESS THAN HUNDREDS OF KILOMETERS

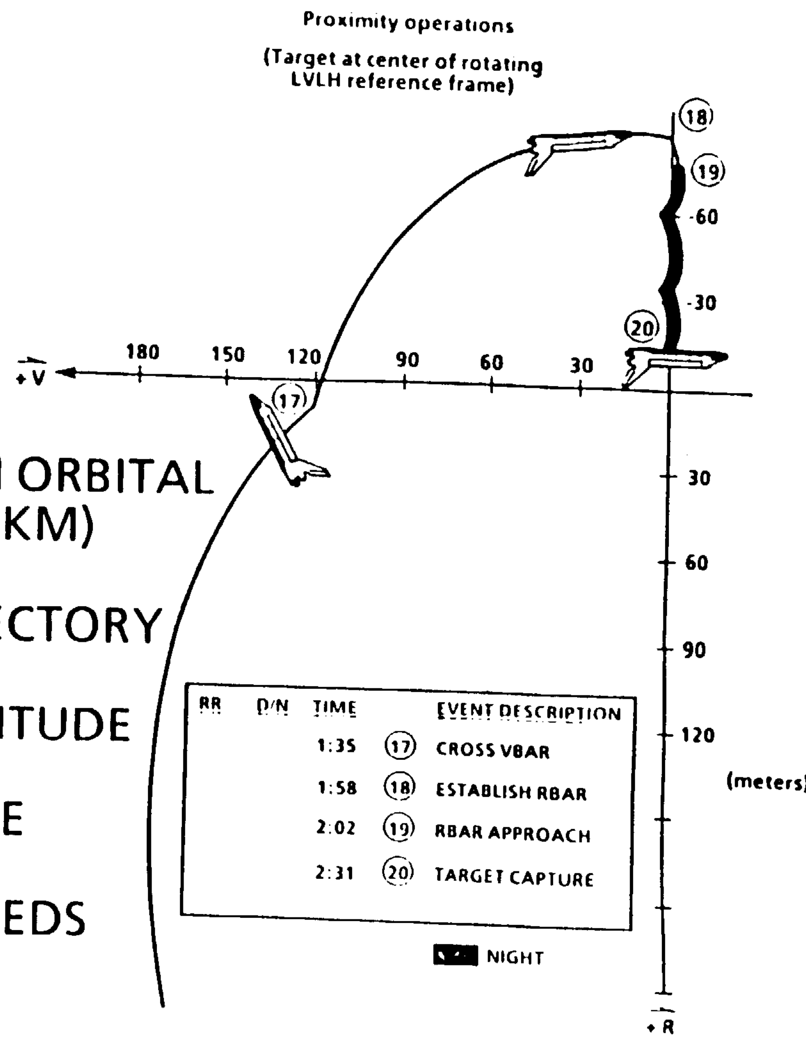
* CHASER MAY TRANSMIT/RECEIVE SIGNAL OR JUST RECEIVE
    ** RADAR, LASER IS 2 – WAY
    ** STAR TRACKER, INFRARED DETECT IS 1 – WAY

* MANEUVERS USUALLY PLANNED TO ATTAIN "OFFSETS" RELATIVE TO THE TARGET AND OCCUR < 1 REV APART



RENDEZVOUS FLIGHT PHASES : CHARACTERISTICS

4. PROXIMITY OPERATIONS FLIGHT PHASE



LDEF retrieval plans.

* OPERATIONAL CONSIDERATIONS OTHER THAN ORBITAL MECHANICS BEGIN TO DOMINATE (RANGE < 1 KM)

* TARGET SIZE/CHARACTERISTICS AFFECT TRAJECTORY CONTROL PLANS
  ** ALIGNMENT FOR DOCKING : TARGET ATTITUDE MODE
  ** EXTENDED STRUCTURES ON TARGET TO BE AVOIDED
  ** CHASER VEHICLE PLUME IMPINGMENT NEEDS TO BE DIRECTED AWAY, SUPPORT DISPERSIONS

* MANEUVERS FREQUENT (MINUTES to SECONDS) AND SMALL (M/S to CM/SEC)

RENDEZVOUS FLIGHT PHASES : CHARACTERISTICS

5. DOCKING

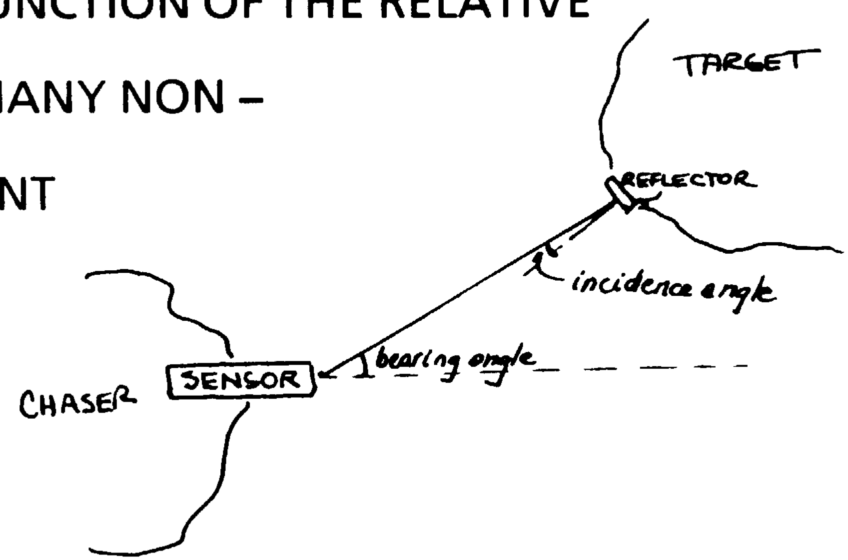
- RANGE $<$ 1 METER
- ORBITAL MECHANICS NEGLECTED
- ESSENTIALLY CLASSICAL DYNAMICS OF RIGID BODIES, LINEAR/ANGULAR MOTION

REMAINDER OF THIS PAPER CONCENTRATES ON

PERFORMANCE REQUIRMENTS FOR THE RELATIVE NAVIGATION and PROXIMITY OPERATIONS FLIGHT PHASES

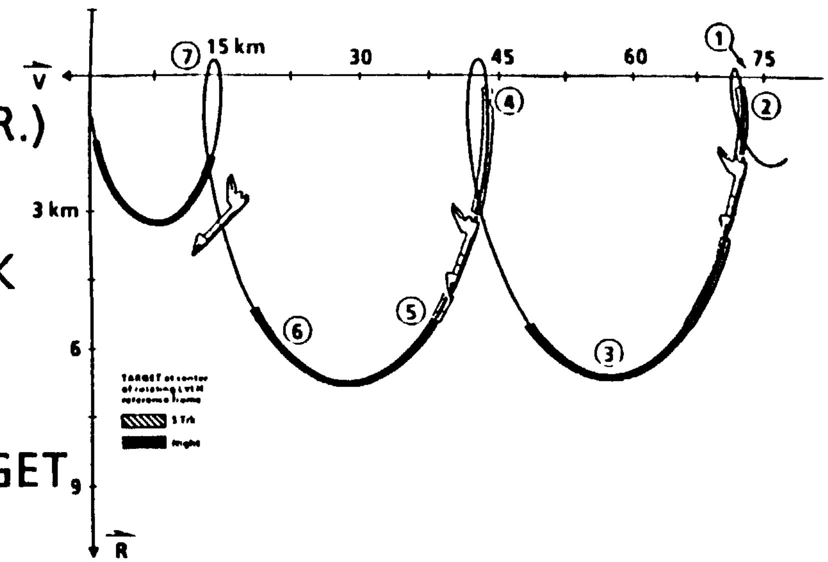
* AGAIN, REQUIREMENTS DEPEND OF ASSUMPTIONS OF ADJOINING FLIGHT PHASES

* REQUIREMENTS ARE A STRONG FUNCTION OF THE RELATIVE MOTION PROFILE
    ** PROFILE CAN DEPEND ON MANY NON – TRAJECTORY CONSTRAINTS
    eg: TIME, POWER, PROPELLANT



TWO PROFILES CONSIDERED TO GIVE INSIGHT INTO PERFORMANCE REQUIREMENTS:

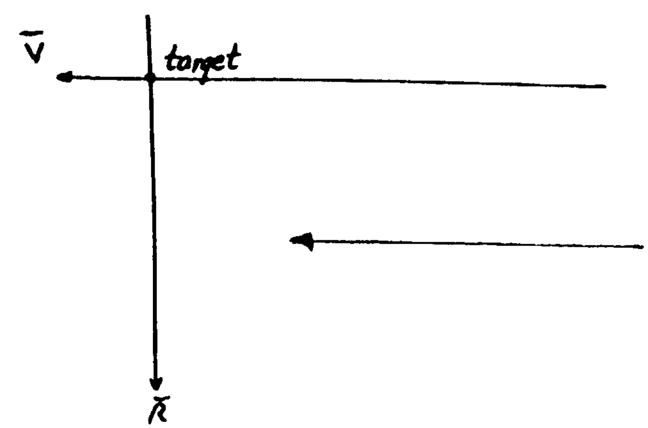
1. SHUTTLE STANDARD "STABLE ORBIT RNDZ" (S.O.R.) PROFILE



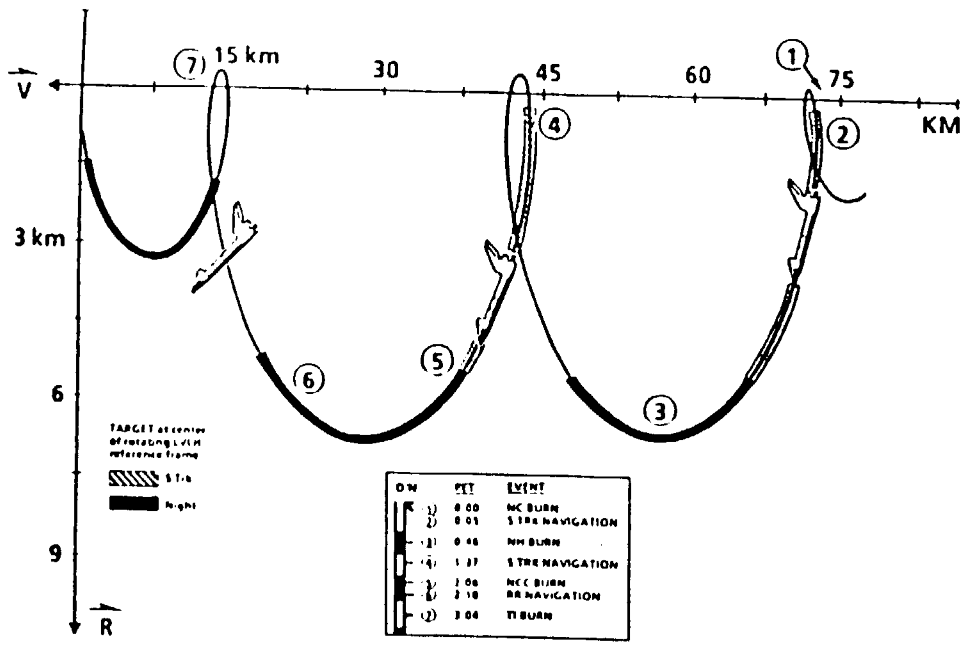
* HANDOFF FROM GROUND TRACKING NETWORK (GSTDN,TDRSS)
  ** TYPICAL SHUTTLE TRACKING DURING RENDEZVOUS OPERATIONS
  ** TYPICAL SKIN TRACKING OF "QUIET" TARGET VEHICLE

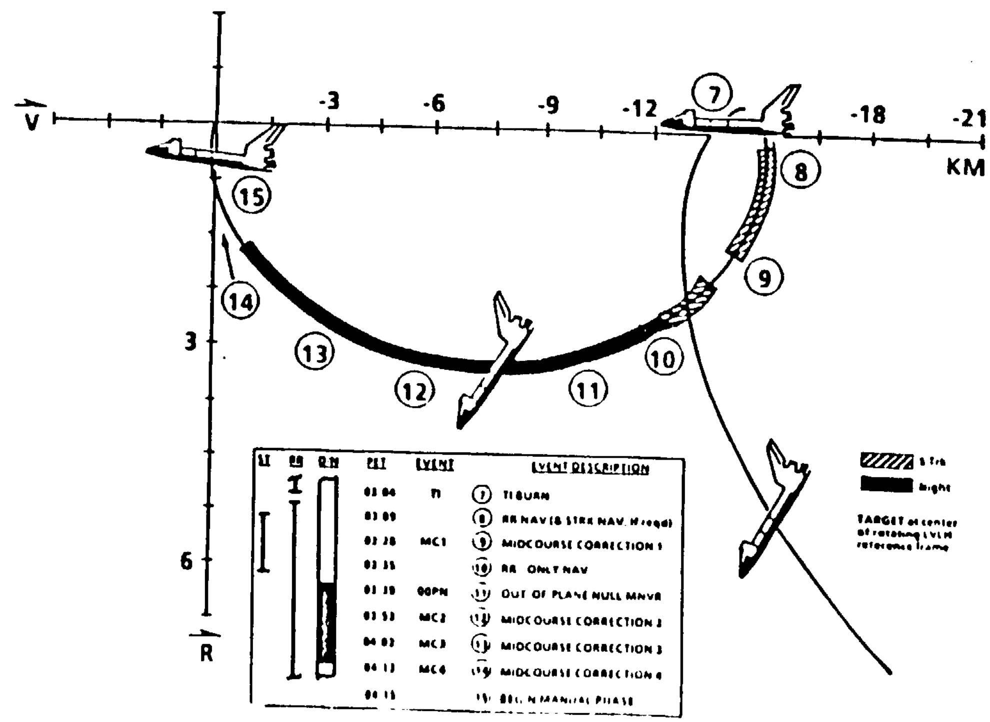
* RELATIVE NAV SENSORS:
  ** STAR TRACKER
  ** RENDEZVOUS RADAR (R < 40 KM)

2. COELLIPTIC PROFILE SEGMENTS



Rendezvous profile

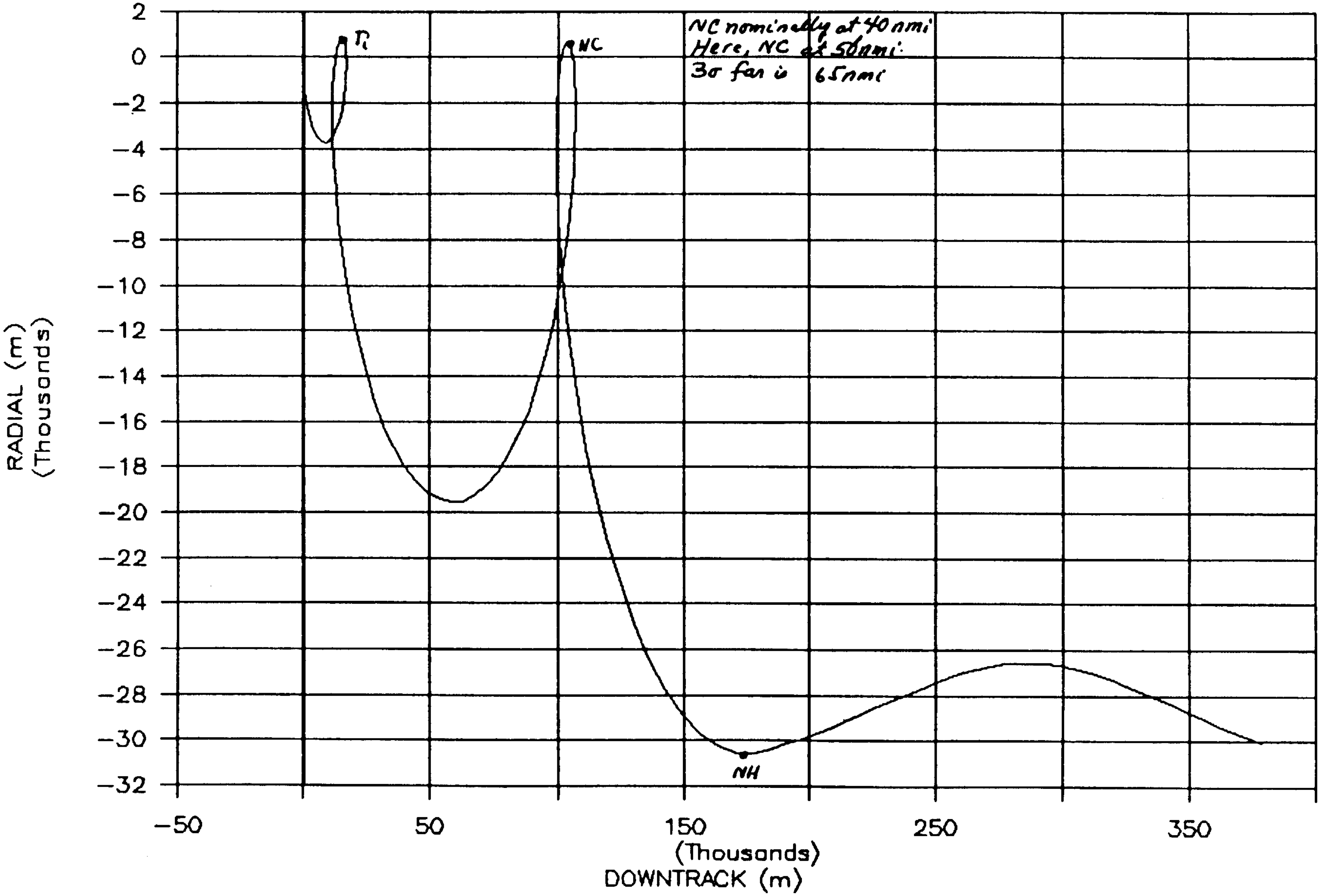




Stable orbit rendezvous profile.

GGU DATABASE

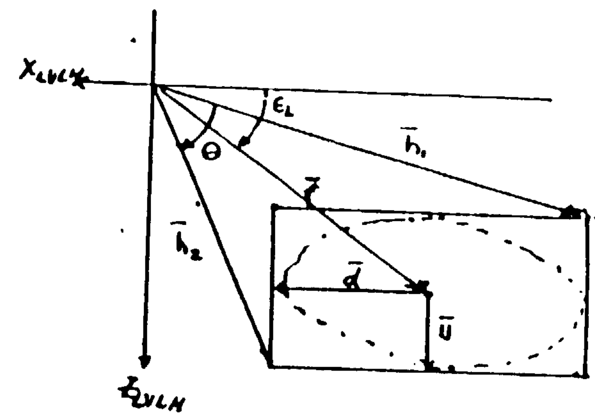
INPLANE RELATIVE MOTION



ACQUISITON SUBPHASE:

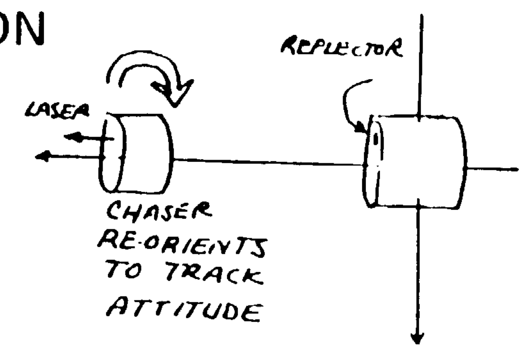
* LONG RANGE INITIAL ACQUISITION FOR RNDZ OPERATIONS

3 deg X 0.5 deg X 10 km at 200 km range
6 deg X 0.7 deg X 10 km at 100 km range
10 deg X 2.0 deg X 10 km at 50 km range



* POST – DEPLOY INITIAL ACQUISITION FOR SEPARATION

24 deg X 24 deg X 7 meters



RANGE MEASUREMENTS:

LIMITS:

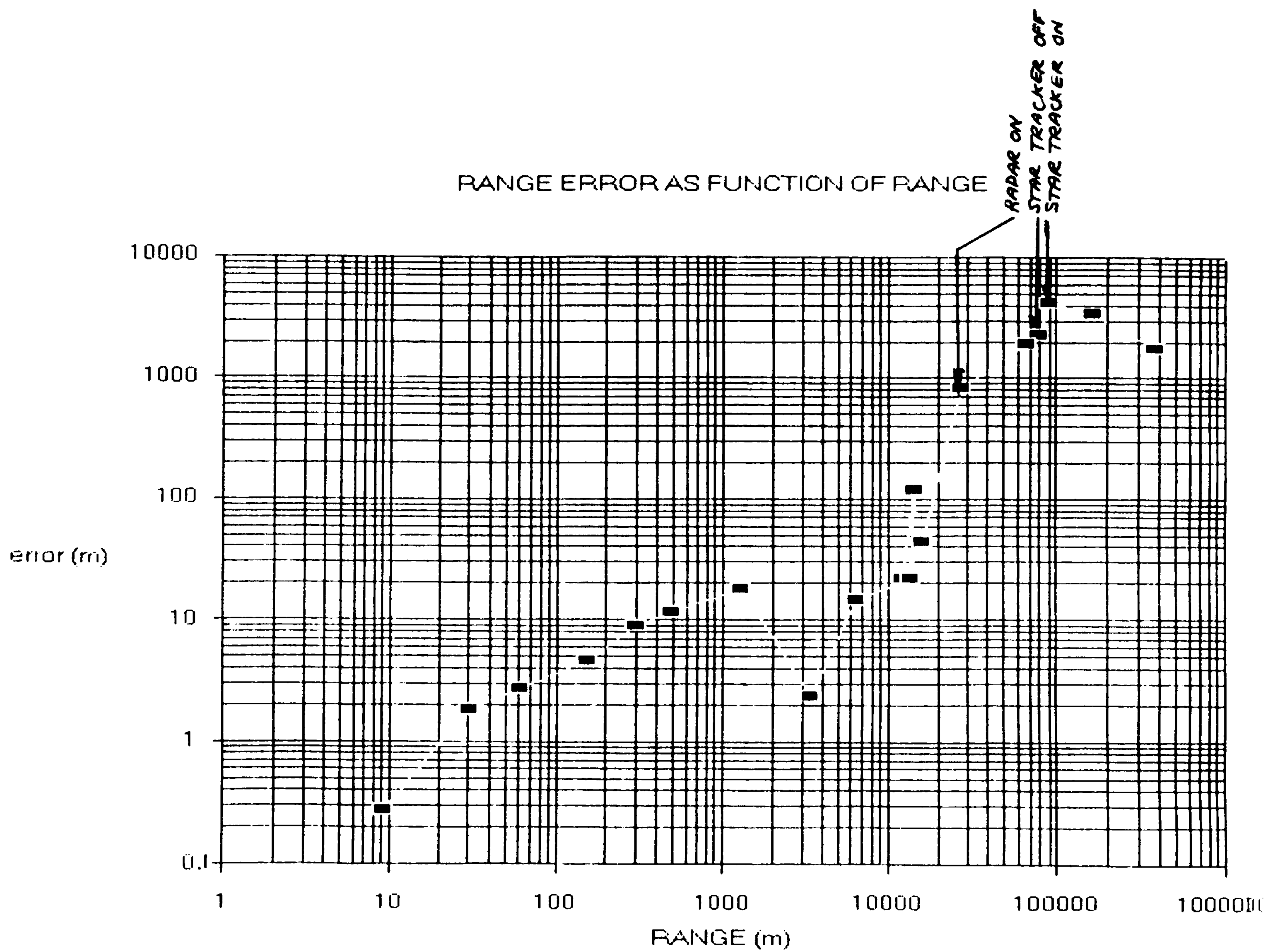
* 0.5 m to 200 km
  ** ACCOMMODATES STS DISPERSIONS AT "NC" WITH ONBOARD TRACKING TO SUPPORT "NC"
  ** SUPPORTS TSS – 2 200 KM TETHER OPERATIONS

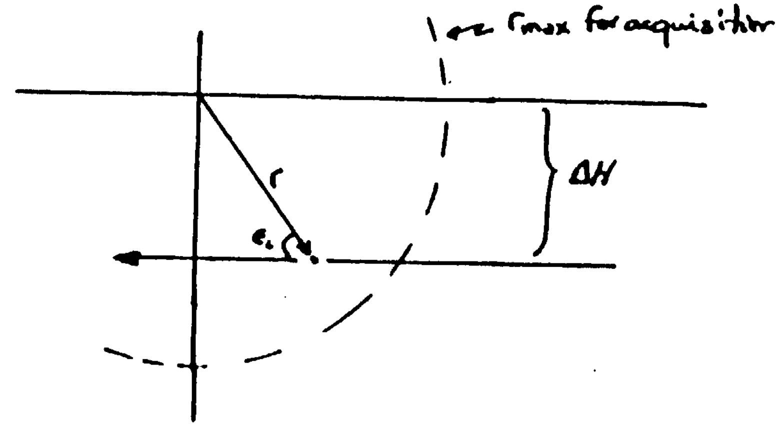
  ** CLOSE RANGE LIMIT ALLOWS FOR SOME SENSOR – REFLECTOR SEPARATION

ACCURACIES (3 SIGMA):

* FROM S.O.R. PROFILE

RANGE ERROR AS FUNCTION OF RANGE





RANGE RATE MEASUREMENTS:

LIMITS:

* FOR LONG RANGES (r > 50km) LIMITS DETERMINED THROUGH COELLIPTIC CONSIDERATIONS

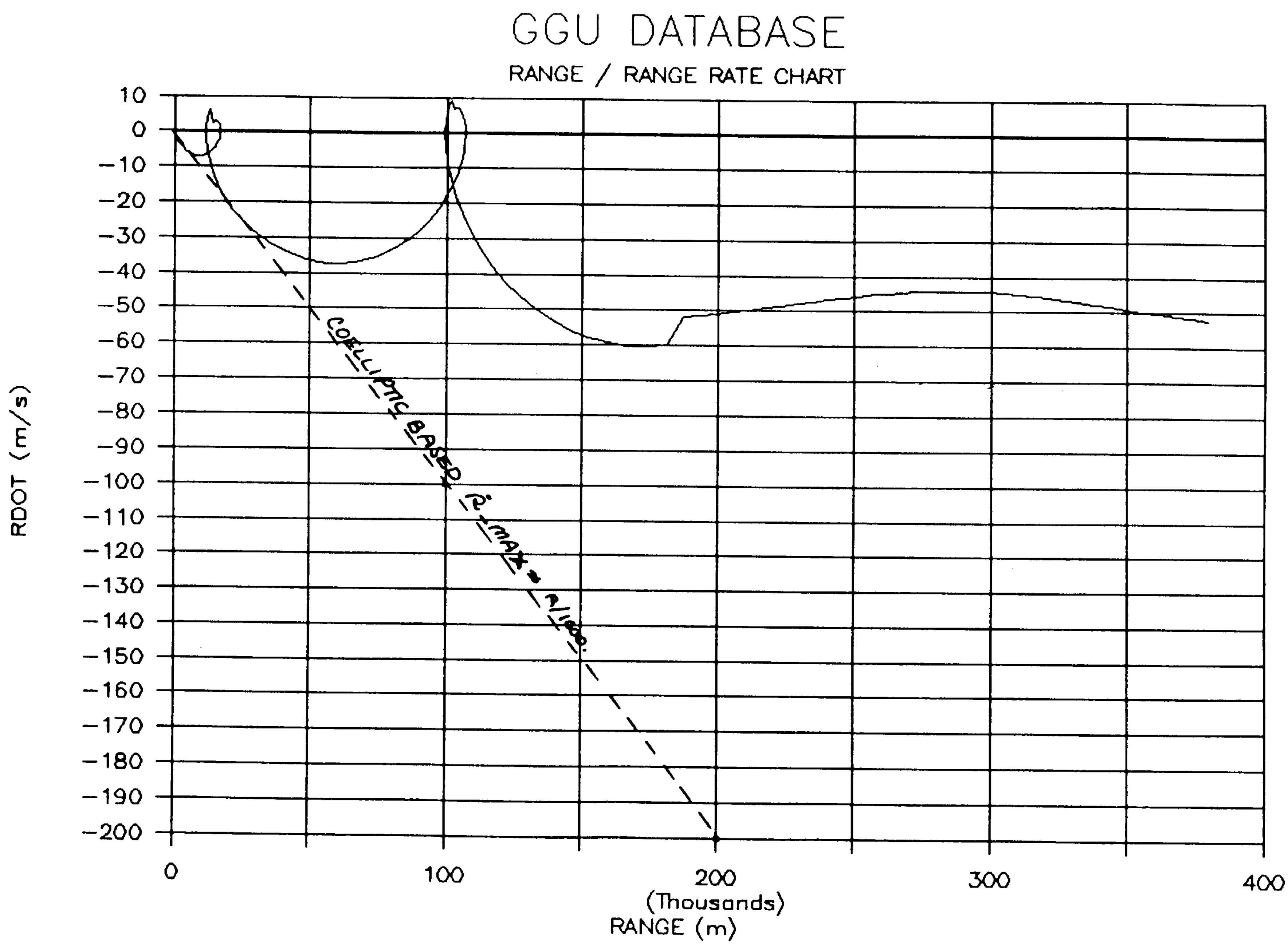
  r – dot   max (m/s) : = range(km)

* S.O.R. PROFILE DOMINATES AT SHORTER RANGES (r < 50km)

  r – dot – max(m/s) : = – 0.9 * range(km) – 5

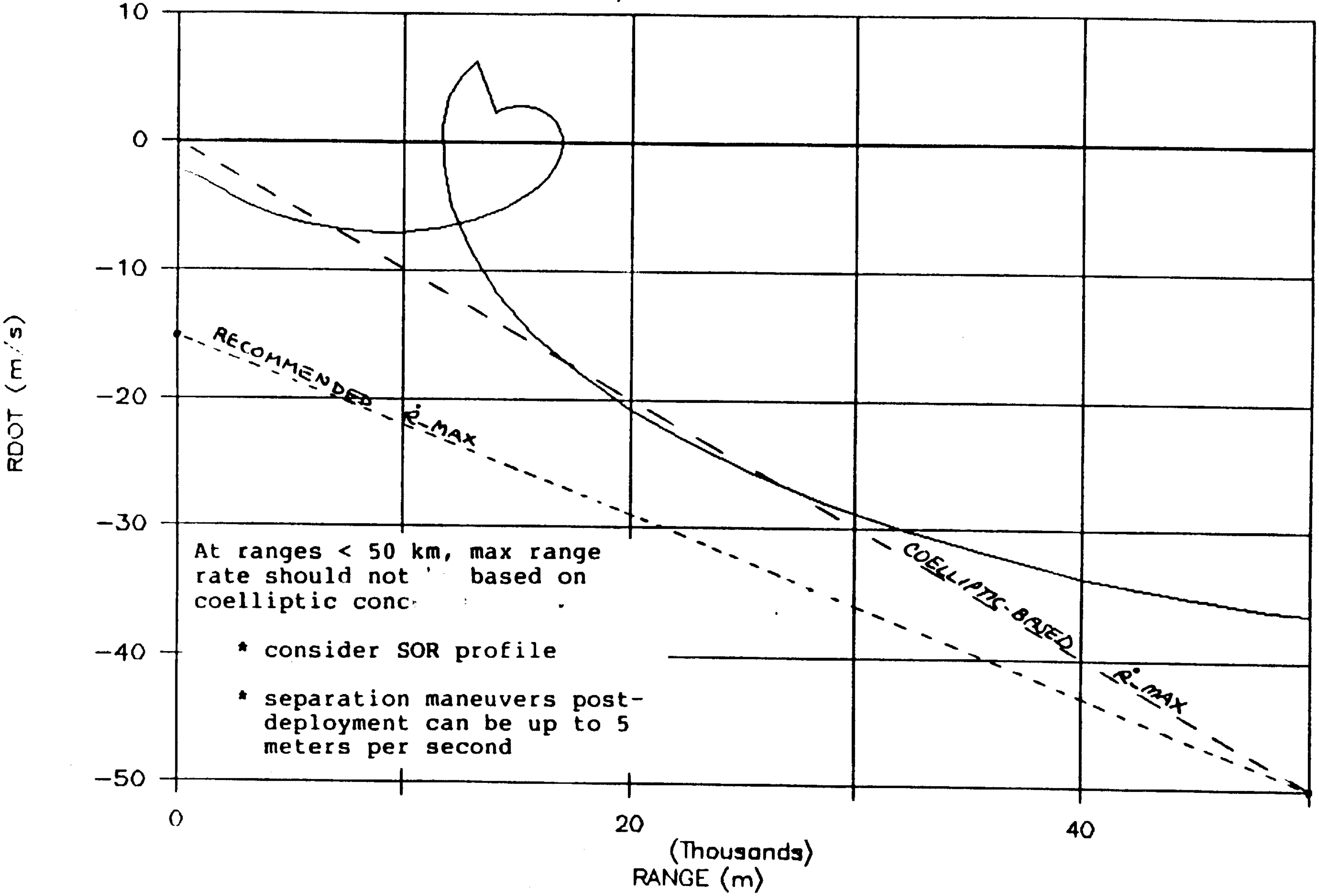
ACCURACIES (3 SIGMA):

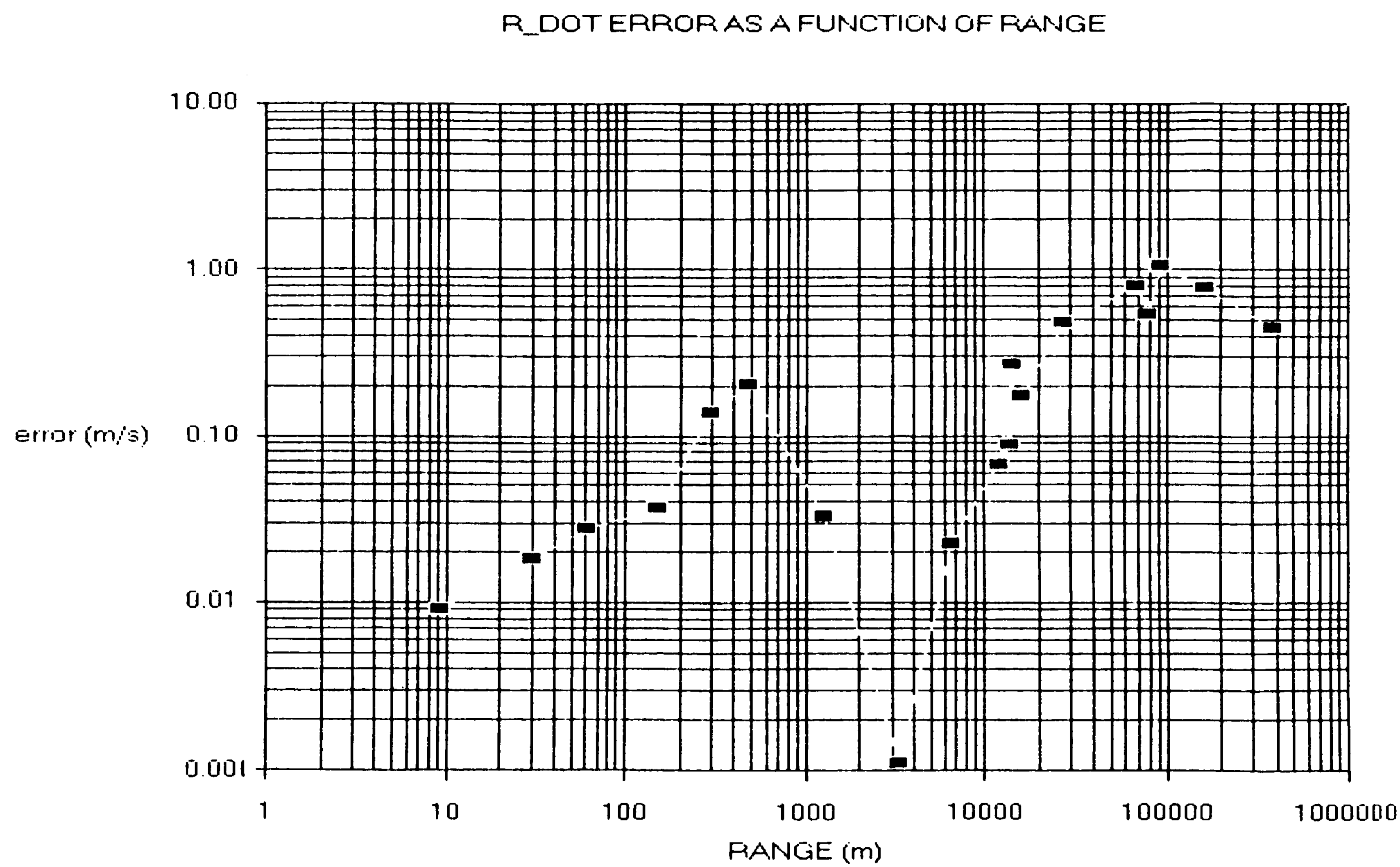
* BASED ON S.O.R. PROFILE WITH NOMINAL ST/RR SENSOR SUPPORT


GGU DATABASE
RANGE / RANGE RATE CHART
RDOT (m/s)
10
0
−10
−20
−30
−40
−50
−60
−70
−80
−90
−100
−110
−120
−130
−140
−150
−160
−170
−180
−190
−200
0
100
200
300
400
(Thousands)
RANGE (m)
COELLIPTIC BASED Ṙ MAX = R/1000.

GGU DATABASE

RANGE / RANGE RATE CHART



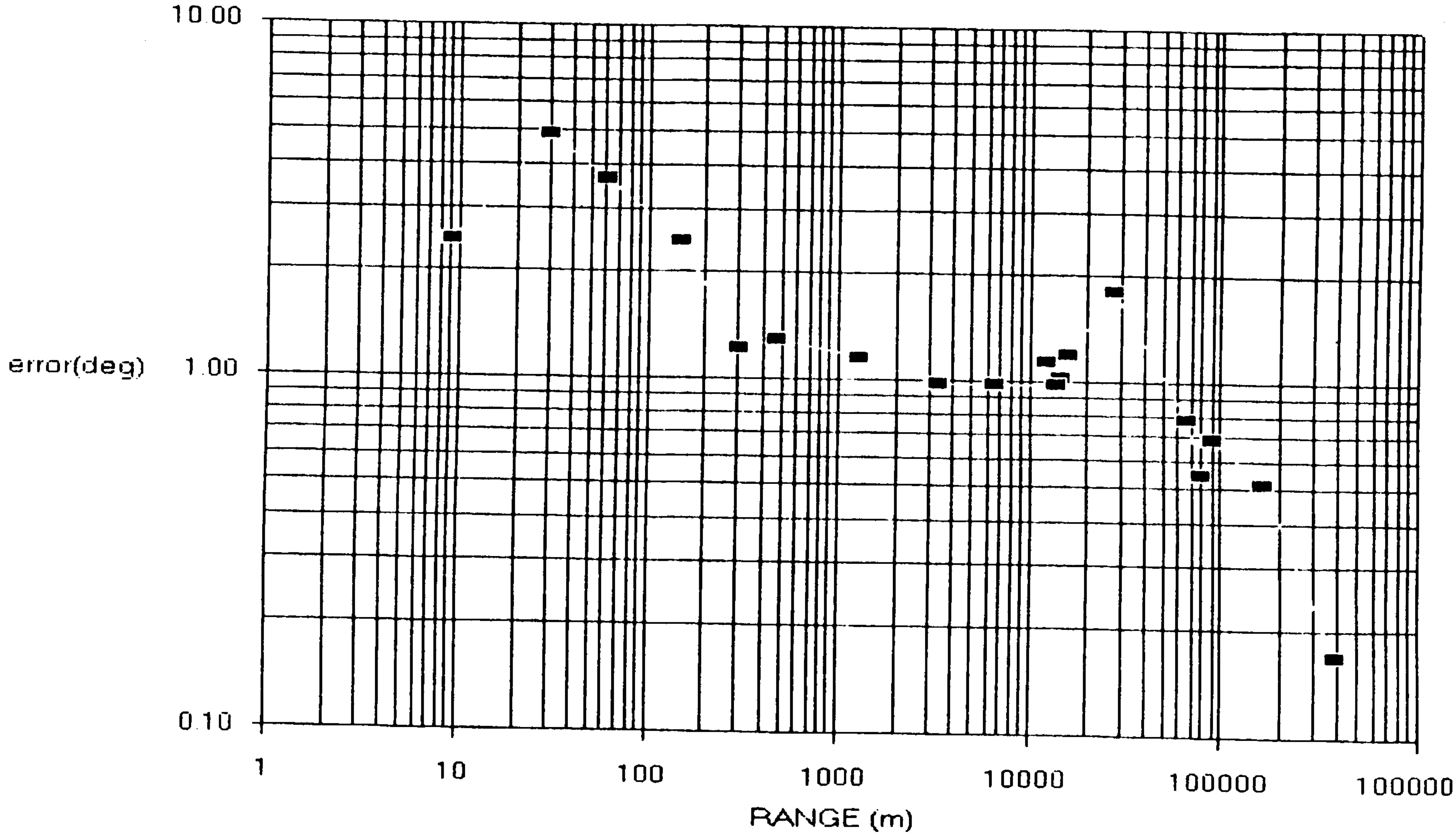

R_DOT ERROR AS A FUNCTION OF RANGE
error (m/s)
10.00
1.00
0.10
0.01
0.001
1
10
100
1000
10000
100000
1000000
RANGE (m)

BEARING ANGLE MEASUREMENTS

LIMITS:
DEPEND ON CHASER POINTING CONSTRAINTS

ACCURACIES (3 SIGMA) :
BASED ON S.O.R. PROFILE

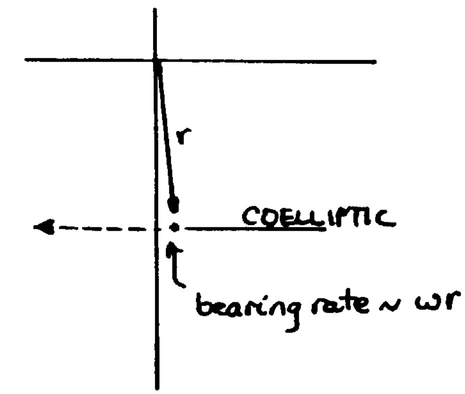
BEARING ERROR AS A FUNCTION OF RANGE



BEARING RATE MEASUREMENTS:

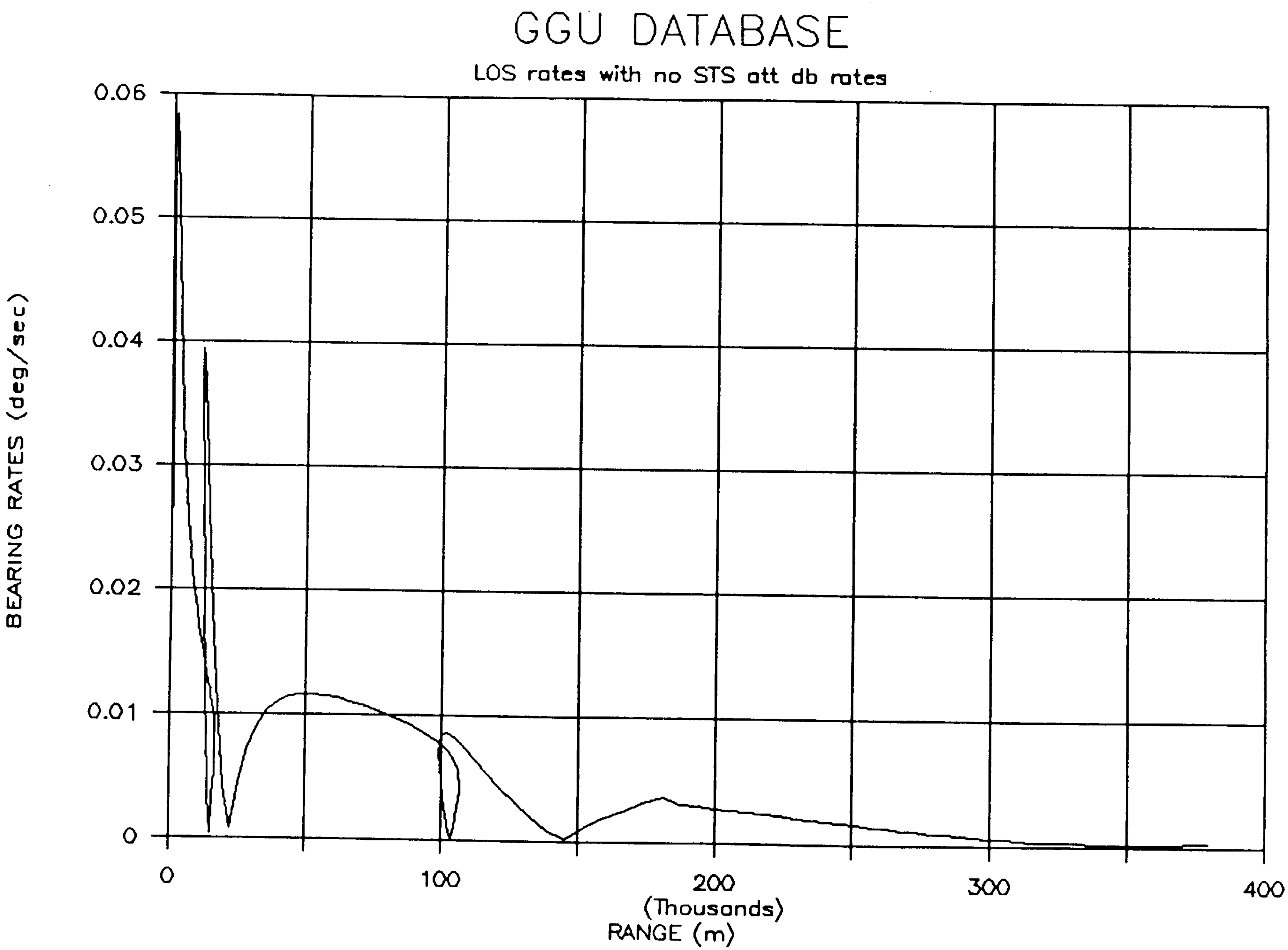
LIMITS:

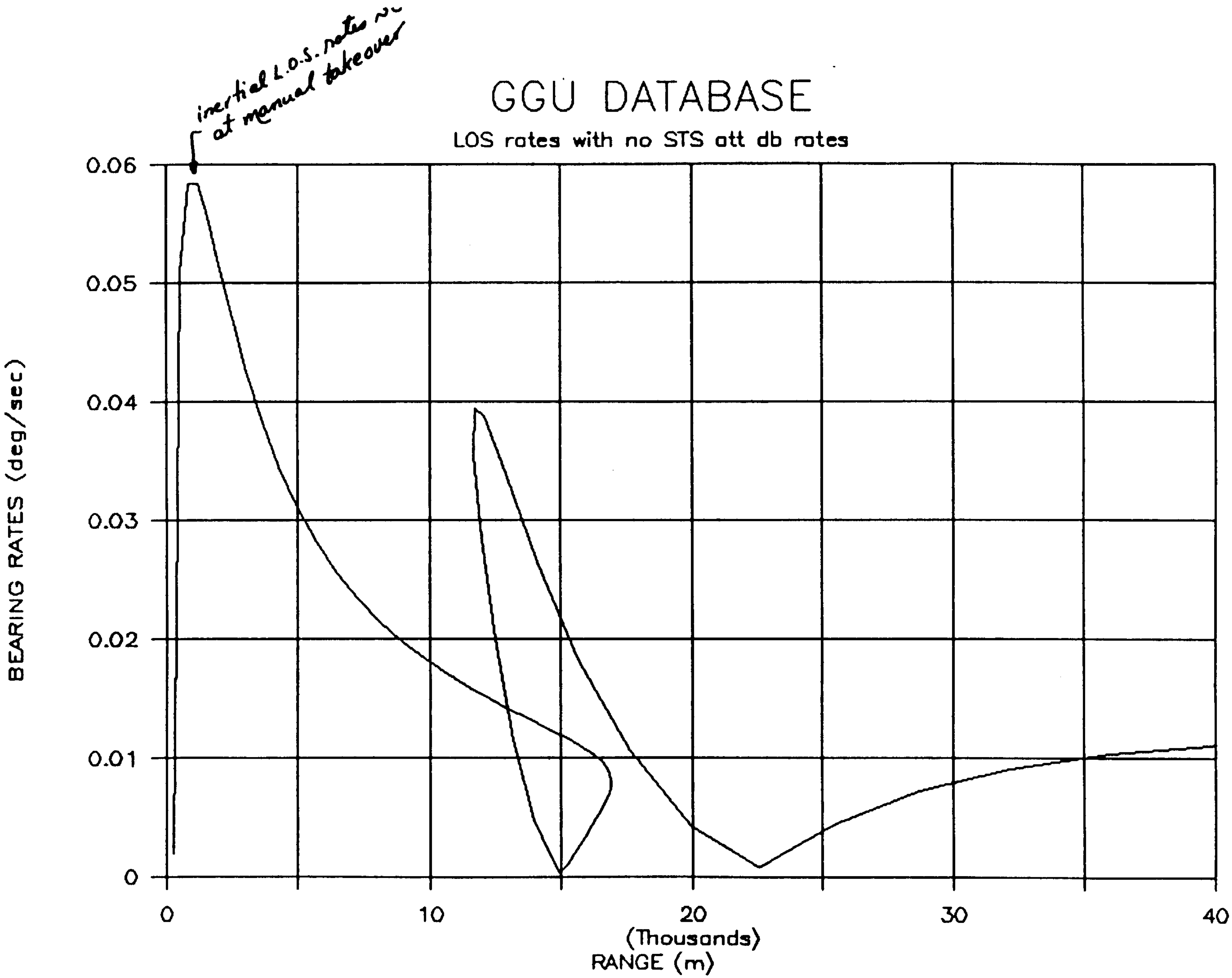
* TYPICAL S.O.R. BEARING RATES < 0.06 DEG/SEC
* COELLIPTIC FLIGHT SEGMENT HAS RATES AS HIGH AS 0.1 DEG/SEC
* CHASER VEHICLE ATTITUDE RATES NEED TO BE APPLIED TO ABOVE LEVELS (0.2 DEG/SEC FOR STS PRCS)



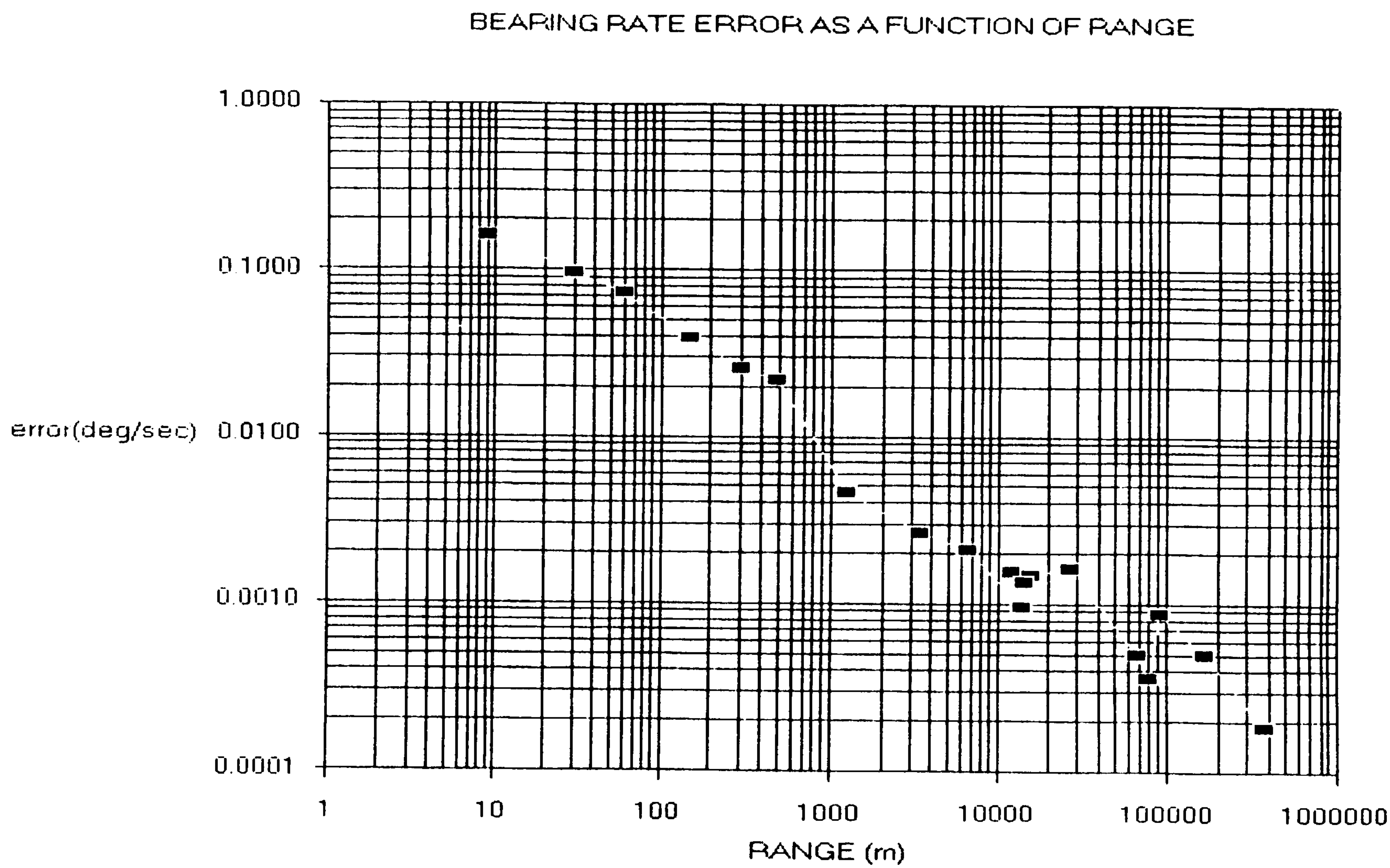
ACCURACIES (3 SIGMA):

BASED ON S.O.R. PROFILE


GGU DATABASE
LOS rates with no STS att db rates
BEARING RATES (deg/sec)
0.06
0.05
0.04
0.03
0.02
0.01
0
0
100
200
300
400
(Thousands)
RANGE (m)



GGU DATABASE
LOS rates with no STS att db rates
inertial L.O.S. rates ~~ at manual takeover
BEARING RATES (deg/sec)
0.06
0.05
0.04
0.03
0.02
0.01
0
0
10
20
30
40
(Thousands)
RANGE (m)


BEARING RATE ERROR AS A FUNCTION OF RANGE
error(deg/sec)
1.0000
0.1000
0.0100
0.0010
0.0001
1
10
100
1000
10000
100000
1000000
RANGE (m)

SUMMARY

* SEVERAL RNDZ FLIGHT PHASES EXIST, AND PERFORMANCE REQUIRMENTS FOR EACH PHASE DEPEND ON

  ** HANDOFF CONDITIONS FROM PREVIOUS PHASE

  ** HANDOFF REQUIREMENTS FOR NEXT PHASE

* PERFORMANCE REQUIREMENTS FOR THE RELATIVE NAVIGATION AND PROX OPS FLIGHT PHASES DEPEND MARKEDLY ON THE PROFILE

  ** ONE SOURCE OF INSIGHT INTO THESE PERFORMANCE LEVELS IS THE SPACE SHUTTLE S.O.R. PROFILE

  ** COELLIPTIC CONSIDERATIONS CAN DRIVE RATE LIMITS

* ONE MUST CONSIDER THESE DEPENDENCIES ON FUTURE SENSOR REQTS DEFINITION

OPERATIONAL REQUIREMENTS AND CONSTRAINTS IN AUTONOMOUS AND REMOTELY CONTROLLED RENDEZVOUS/DOCKING MISSIONS

HANS F. MEISSINGER

FOR PRESENTATION AT

NASA/JSC AUTONOMOUS RENDEZVOUS
AND DOCKING CONFERENCE

AUGUST 15-16, 1990

HOUSTON, TEXAS

INTRODUCTION

Remotely controlled rendezvous/docking sequences are subject to stringent constraints on target detection and tracking conditions and two-way orbit to ground communication characteristics in the feedback control loop. Relay link delays and operator perception lag affect remote control performance.

Fully autonomous control avoids these constraints and ideally would provide uninterrupted rendezvous/docking opportunities, around the clock. In practice, remote monitoring and supervisory control of unmanned satellite rendezvous and docking sequences by a ground-based operator may still be desirable, at least as a transitional step before full autonomy is to be introduced, and thus imposes some of the above constraints.

This paper outlines the sensing, viewing and communication and control requirements that apply at various levels of rendezvous/docking autonomy, and presents results of comprehensive analyses of the underlying orbital geometry, orbital mechanics, proximity operations and control system characteristics. Of particular interest are the implications on mission timelines, and permissible daily rendezvous/docking windows.

The material presented is based, in part, on studies performed under NASA/MSFC Contract NAS8-36800, covering the development by TRW of the Orbital Maneuvering Vehicle (OMV), and in particular, our Remote Tanker/Servicer and Autonomous Docking Studies (Ref. 1, 2).

TOPICS

- AUTONOMOUS RENDEZVOUS/DOCKING PROFILE
- FACTORS IN REMOTE AND AUTONOMOUS CONTROL
- TIME DELAY EFFECTS IN REMOTE, HUMAN OPERATOR CONTROL
- TARGET SPACECRAFT ORIENTATION FACTORS
- SENSOR COMPLEMENT
- SUN ILLUMINATION CONSTRAINTS
- COMMUNICATION COVERAGE BY RELAY LINK
- DAILY RENDEZVOUS WINDOWS
- REQUIREMENTS AND CONSTRAINTS SUMMARY

RENDEZVOUS AND DOCKING CONTROL SCENARIO

As a point of departure, the control scenario assumes automated rendezvous based on GPS navigation and radar data, to a nominal target distance of 1000 ft. From here, the terminal approach and docking phase is controlled remotely from a ground control console (GCC) by commands transmitted by a human operator via TDRSS link. The operator receives feedback data from OMV's docking camera(s) and from telemetry of range, range rate, angle and angle rate information, a least during the major part of the terminal approach, as long as commensurate with radar performance. During the final approach, nominally within about 50 ft of the target, the operator relies entirely on the data presented on his video monitor that indicate range and angular alignment.

Addition of auto-docking capability permits docking without the need for the communication link and human operator control:

- The adverse effect of communication time delay, nominally 3 sec, in the control loop is avoided.
- Automated control responds instantly to multiple channel error signals.
- Rendezvous and docking can be completed faster and generally at lower propellant consumption.
- The work load for GCC operators is greatly reduced.

The control capability of the initially assumed manual docking system is still available to provide for manual override of the automated approach if necessary.

To provide this capability, the navigation and control channels of the "chaser" vehicle are modified to incorporate an onboard docking sensor and to accommodate its output data. Sensor characteristics must meet auto-docking accuracy requirements and operational constraints.

AUTONOMOUS VS REMOTE CONTROL OF R/D SEQUENCE

1. REMOTE CONTROL

- GROUND CONTROL STATION, VIDEO IMAGE DISPLAY
- HUMAN PILOT ACTIONS AND LIMITATIONS
- TIME LAG EFFECTS AND COMPENSATION
- TV VIEWING AND RELAY LINK COVERAGE CONSTRAINTS

2. AUTONOMOUS CONTROL

- FULLY AUTONOMOUS R/D SENSING
- MULTIPLE CHANNEL RESPONSE
- AVOIDANCE OF SUN ILLUMINATION AND RELAY LINK CONSTRAINTS
- COLLISION AVOIDANCE

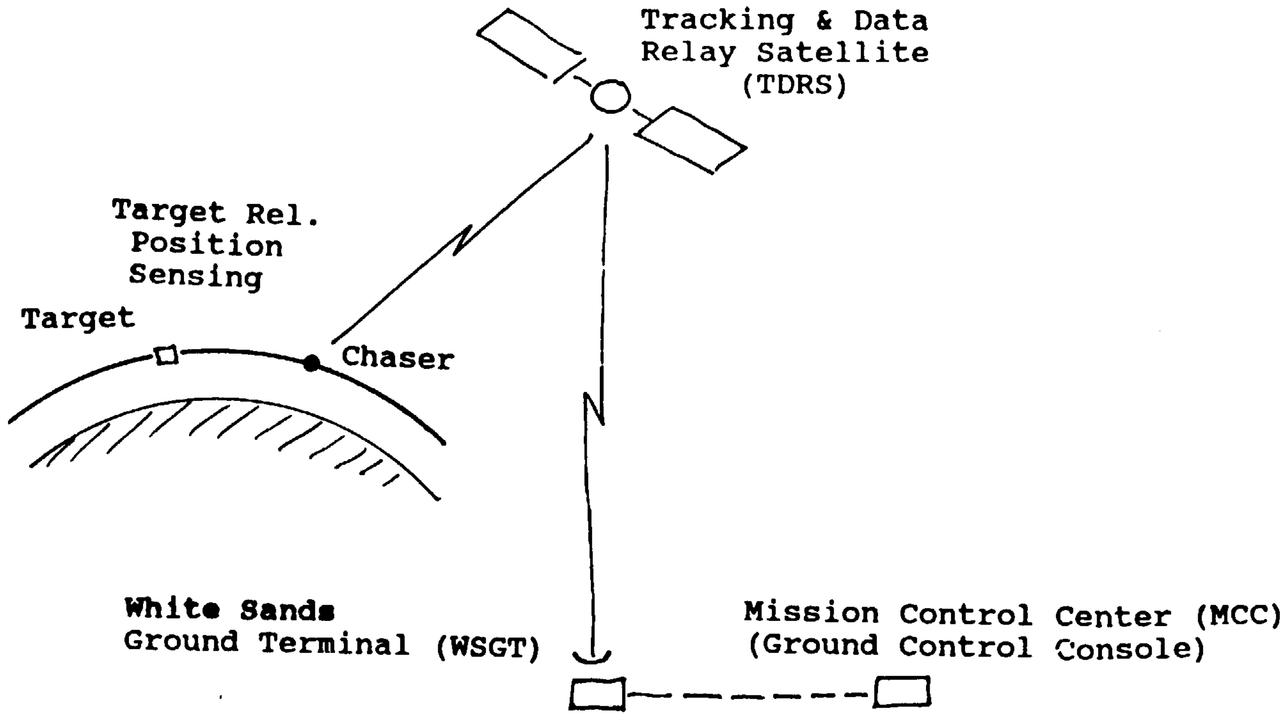
3. SUPERVISED, SEMI-AUTONOMOUS CONTROL

- PROVIDES TRANSITIONAL CAPABILITY BEFORE FULL AUTONOMY IMPLEMENTATION
- BENEFITS AND CONSTRAINTS OF MODES 1 AND 2
- EVOLUTIONARY STEP BEFORE ADOPTION OF NOVEL TECHNOLOGY

REMOTE RENDEZVOUS/DOCKING CONTROL VIA TDRSS RELAY

Relay communication via the Tracking and Data Relay Satellite System (TDRSS) is an essential link in remote rendezvous/docking control from the ground, but also is needed for supervised autonomous rendezvous and docking. In addition to the signal path via the TDRS satellite, relay communication, via a domestic comsat, between the ground control console and the TDRSS ground terminal also may be required. This would increase the number of signal round trips to and from synchronous orbit altitude from 2 to 4. Full control autonomy avoids the signal delay due to relay transmission, and its potential degradation of the feedback control system performance. It also eliminates the human operator's perception lag and his slower response to control errors in six degrees of freedom, compared with the autonomous simultaneous system response in all control channels.

REMOTE RENDEZVOUS/DOCKING CONTROL VIA TDRSS RELAY



- TIME DELAY IN FEEDBACK CONTROL LOOP DUE TO TDRSS LINK (TWO SIGNAL ROUND TRIPS) AND HUMAN OPERATOR PERCEPTION LAG
- 2 ADDITIONAL SIGNAL ROUND TRIPS IF DOMESTIC COMSAT IS USED BETWEEN WSGT AND MCC (NOT SHOWN IN FIGURE)
- FULL CONTROL AUTONOMY ELIMINATES THE CUMULATIVE TIME DELAY, THUS PERMITS FASTER CONTROL RESPONSE AND AVOIDS SUSCEPTIBILITY TO OUTAGE

TIME DELAY EFFECT ON REMOTE HUMAN CONTROL PROCESS

As outlined in the chart, time delay in the feedback control loop is introduced by the relay link between ground control and chaser (about 3 sec of round trip delay) and the human control operator's perception lag (estimated to be 2 to 5 seconds). The perception lag decreases with target distance, since the target's image and its relative motion as displayed on the video screen are becoming larger.

The phase lag in control response due to pure time delay tends to destabilize the control system behavior. In the limit, for a given time delay and a sufficiently high frequency content of the control input the effective phase lag could be as large as 180° and cause instability. In actual remote control simulations with time delay, an experienced operator slows down his input commands to an equivalent driving frequency of at most 0.05 to 0.10 cps, i.e., he allows 10 to 20 sec between command pulses to avoid destabilizing effects.

Predictive display techniques may ease the control task and permit faster completion of the docking approach and would be worth exploring. Control simulations performed at MIT and JPL with time delays between 3 and 10 seconds show a marked improvement of control accuracy, speed and repeatability.

TIME DELAY EFFECT ON REMOTE, HUMAN CONTROL PROCESS

1. TIME DELAY SOURCES

- TDRSS RELAY INTRODUCES ABOUT 3 SEC ROUND TRIP DELAY (UP TO 650 MSEC FORMATTING AND ROUTING DELAYS AT WHITE SANDS GROUND STATION)
- HUMAN OPERATOR PERCEPTION LAG 2 TO 5 SEC (DEPENDS ON TV IMAGE RESOLUTION AND DYNAMIC RESPONSE TO MANEUVER COMMANDS)

2. DESTABILIZING EFFECT

- STABILITY LIMIT ON COMMAND SIGNAL FREQUENCY

$$2\pi F T_D \leq 2 \text{ RAD}$$

- FOR $T_D = 3$ SEC $F_{LIM} \sim 0.1$ CPS
  $T_D = 6$ SEC $F_{LIM} \sim 0.05$ CPS

3. PRACTICAL IMPLICATIONS

- IN SIMULATED DOCKING STUDIES HUMAN OPERATOR LEARNS QUICKLY TO ACCOMMODATE TIME DELAY EFFECT BY LOWERING HIS COMMAND INPUT FREQUENCY
- POSSIBLE BENEFIT OF PREDICTIVE DISPLAY TO BE EXPLORED

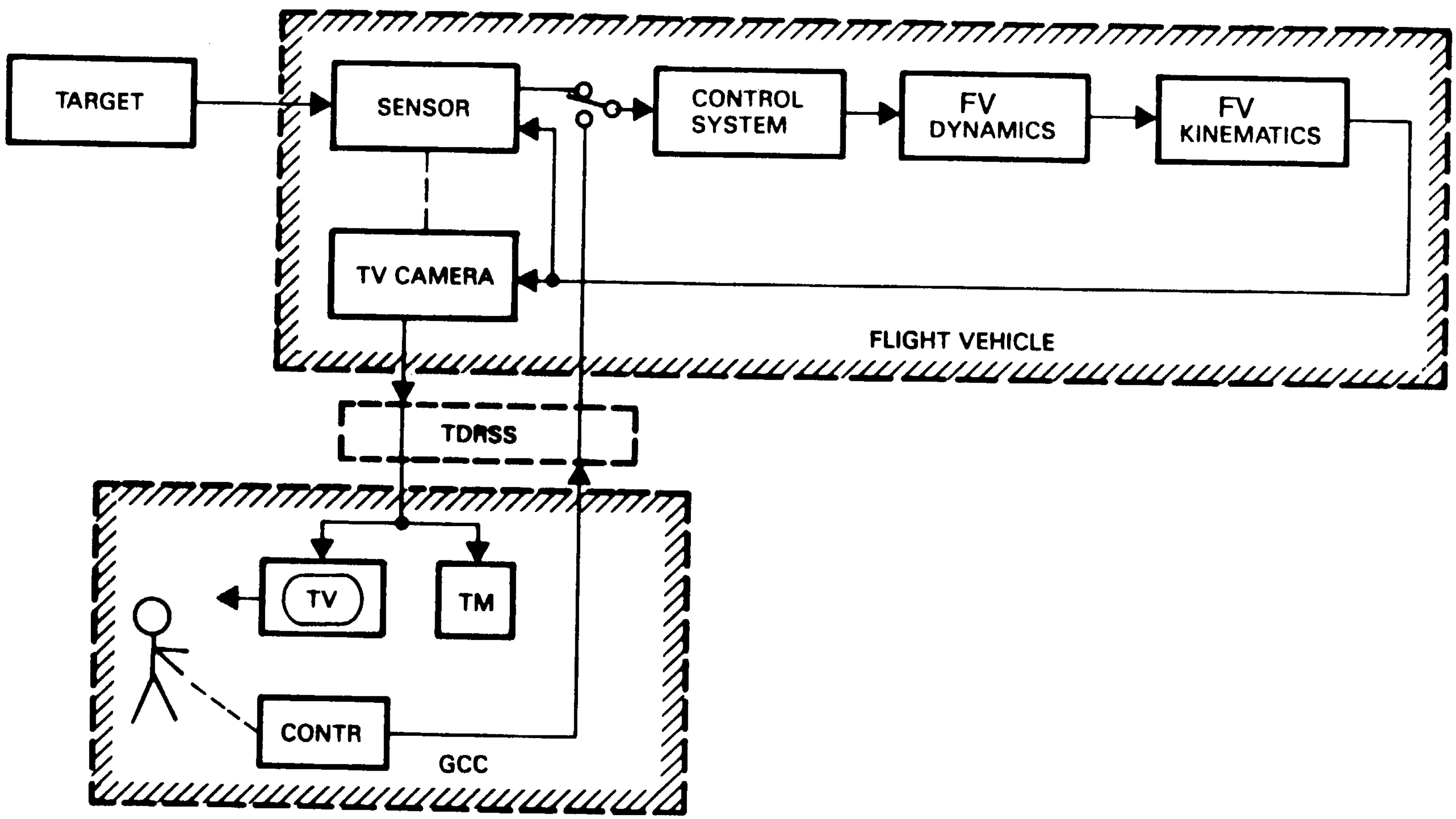
MANUAL AND AUTOMATED DOCKING CONTROL (SIMPLIFIED SCHEMATIC)

The chart shows a schematic diagram of the manual and automated control modes to be used in docking at the target. Manual control provides a convenient backup mode if necessary. This supervised autonomy concept calls for the GCC operator to override automated docking control in case of malfunction or unforeseen contingencies. This requires monitoring of video and telemetry data on the ground during the entire docking procedure, and therefore demands continuous high data rate TDRSS downlink communication.

As autonomous docking evolves as a more routine procedure, this requirement may be replaced by a less demanding one, calling for response from the GCC to emergency alert signals only. The automated system may have provisions for stopping the docking approach during an emergency alert, awaiting ground-based intervention.

Because of the unacceptable risk of damage to the target satellite and/or the chaser due to system failure during the final few minutes of the docking approach and physical docking contact, the supervised autonomy procedure probably will be a mandatory interim requirement, for some time. In addition, a collision avoidance maneuver (CAM) capability must be provided, that will respond automatically in the event of critical hardware or software failures onboard the chaser, or in TDRSS uplink or downlink.

MANUAL AND AUTOMATED DOCKING CONTROL
(SIMPLIFIED SCHEMATIC)



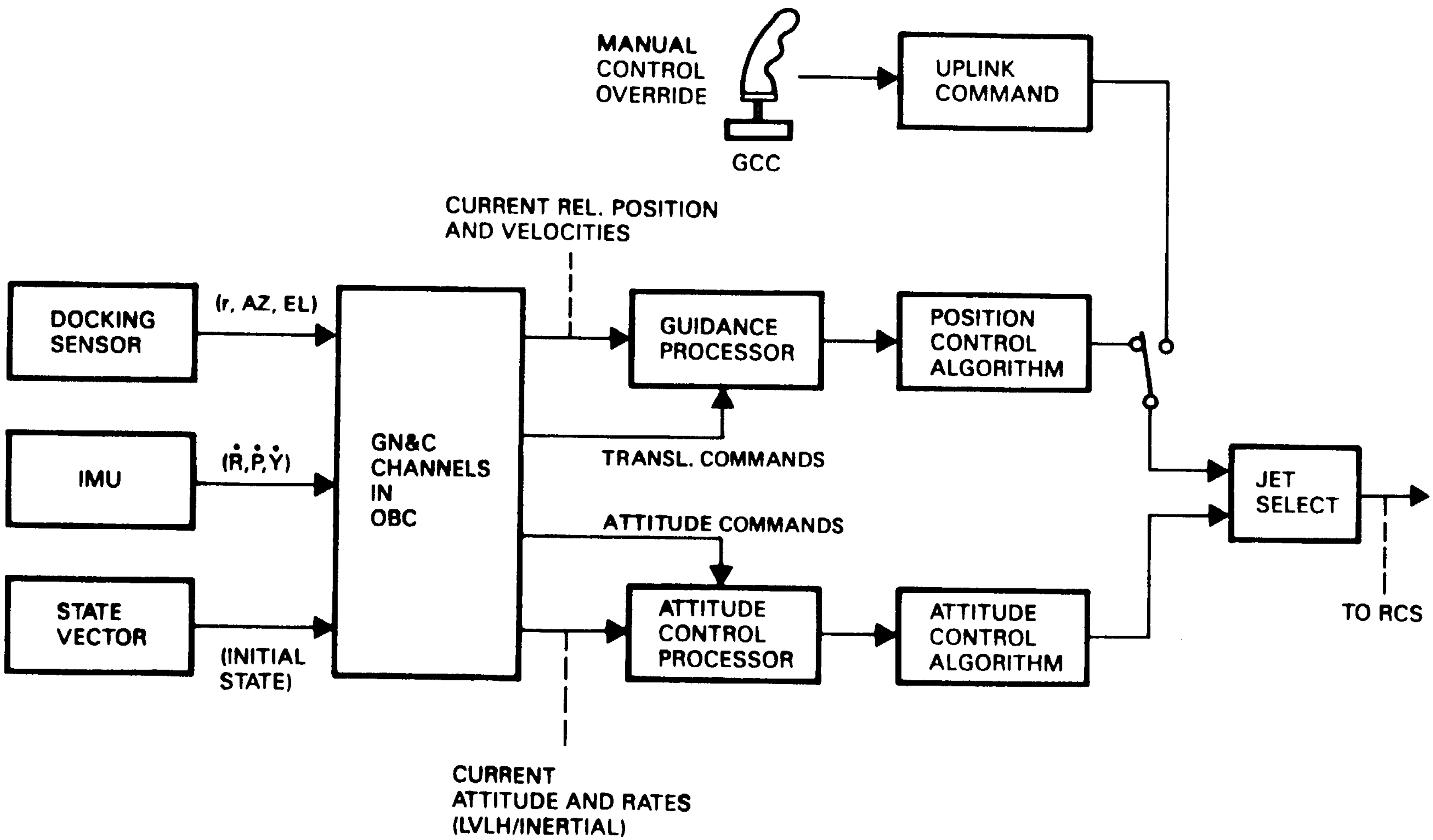
DOCKING CONTROL SCHEMATIC

The chart shows a top-level schematic block diagram of GN&C subsystems elements involved in the implementation of automated docking with manual override capability.

On the left side of the diagram are the inputs to the GN&C channels in the onboard computer (OBC), originating from the docking sensor (TV camera or LDS) and the IMU. In addition, state vector data derived from GPS navigation algorithms, known target position and velocity, radar data and prior results of relative state vector computations, also are fed into the OBC. The data flow includes guidance processor and position control channels on one hand and attitude control processor and attitude control algorithm channels, on the other. Position control and attitude control data are entered into a jet select logic to pick the appropriate control thruster combinations and operating sequences.

Manual control override by uplink command from the GCC is shown as an alternative to the automatic onboard sensor-controlled docking process. It is arranged to replace the OBC-determined position and orientation control channels instantly, as soon as the GCC operator actuates his manual control stick.

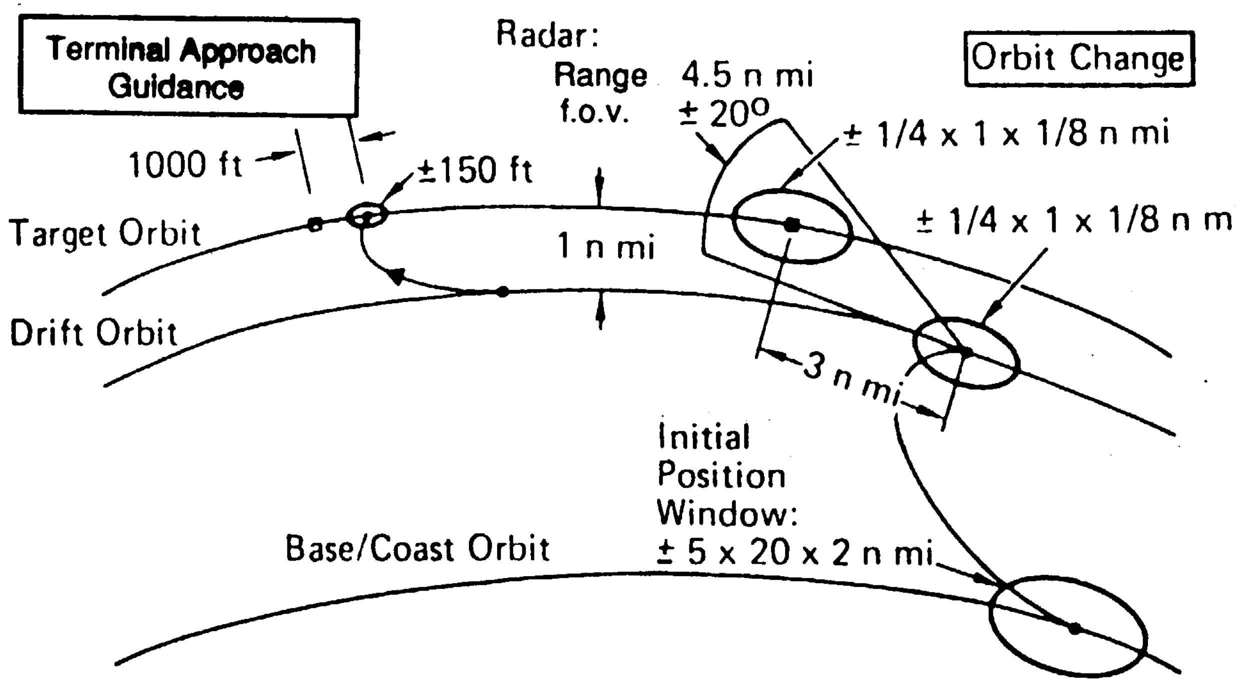
DOCKING CONTROL SCHEMATIC



GN&C CHANNELS AND SENSOR COMPLEMENT

• INERTIAL MEASUREMENT UNIT (IMU) - integrated rate gyro (3 axes) - accelerometers (3 axes)	- Together with on-board computer provides basic autonomous rendezvous GN&C capability. Based on projected and updated target ephemeris
• GPS RECEIVER • GROUND TRACKING (TDRSS) SUPPORT	- With Kalman filtering continuously updates IMU for rendezvous guidance and navigation
• RENDEZVOUS RADAR	- In final rendezvous phase provides 3-DOF relative target position. Range between ~ 5 nm and 35 ft
• TV DOCKING CAMERA(S) WITH SIGNAL PROCESSING	- Used in terminal rendezvous/docking phase, from 1000 ft range. Used by human controller or for autonomous control via video signal processing
• LASER DOCKING SENSOR (LDS)	- Covers entire rendezvous/docking range from 100 nm to final docking contact. Relative position and rotation coordinates (6-DOF) and their derivatives (Being developed under NASA/JSC contract by MDAC.

RENDEZVOUS GUIDANCE AND NAVIGATION



- **RENDEZVOUS MISSION WITH SPECIFIED TARGET ERROR ELLIPSE DIMENSIONS IS G&N REQUIREMENTS DRIVER**
- **THIS AND DESIRE TO MINIMIZE NAVIGATION SENSOR REQUIREMENTS AND COST LEADS TO DERIVED INJECTION ACCURACY REQUIREMENT AT THE 3 NM POINT**
- **± 150 FT ACCURACY REQUIREMENT AT TERMINAL APPROACH INITIATION ACCOMMODATES PILOT CONTROLLED OR AUTONOMOUS DOCKING**

CANDIDATE DOCKING SENSORS

Two typ f range and angle sensing techniques suitable for application to automated docking are currently under development. Candidate sensors are:

(1) Imaging systems such as the OMV docking camera, with appropriate image signal processing that provides relative target range and angle information.

(2) Precision range and angle tracking systems such as the Laser Docking Sensor (LDS) of which an engineering prototype is currently being developed under NASA/JSC contract by McDonnellDouglas.

Both types of docking sensors require active or passive target augmentation to simplify target detection, and range and angle data extraction. Auto-docking is achievable more readily with cooperative targets that support the process by carrying appropriately mounted and configured retro-reflector arrays. The chaser will preferably be equipped with illuminating devices such as laser diodes, to enhance the return signal and permit discrimination between true and false target points in the sensor field of view. Flashing lights arranged in a suitable pattern on the target would further enhance detection and signal extraction capabilities by the docking sensor, and enhance discrimination against false targets.

The principle of range and angle determination by video image processing will be discussed below. The technique has been used extensively in auto-docking simulations performed by Martin Marietta, NASA/MSFC and TRW over the last few years (see References 3, 4 and 5).

The Laser Docking Sensor (LDS) is based on an engineering demonstration model designed and built at NASA/JSC in the early 1980's and incorporates improved target acquisition and tracking characteristics. The sensor provides range and bearing angle data as well as attitude measurements from the reflected beams. Output signals include not only range and angle data but also their rates of change obtained as derived quantities.

CANDIDATE DOCKING SENSORS

DOCKING CAMERA

- T-SHAPED ARRAY OF 3 TARGET POINTS
- ENHANCED BY RETRO-REFLECTORS OR FLASHING LIGHTS
- SAME TARGET CONFIGURATION AS IN MANUAL DOCKING CONTROL
- STADIAMETRIC RANGING
- BEARING ANGLES FROM APPARENT DISPLACEMENT OF CENTROID

LASER DOCKING SENSOR (LDS)

- DESIGN BASED ON MODEL DEVELOPED BY JSC
- FLIGHT DEMO MODEL BEING DEVELOPED BY MDAC
- FIVE-ELEMENT RETRO-REFLECTOR TARGET MODULE
  - RANGE AND BEARING ANGLES: CENTER ELEMENT
  - ATTITUDE ANGLES FROM SQUARE ARRAY OF FOUR OUTER ELEMENTS

RANGE AND ANGLE DETERMINATION FROM TV IMAGE

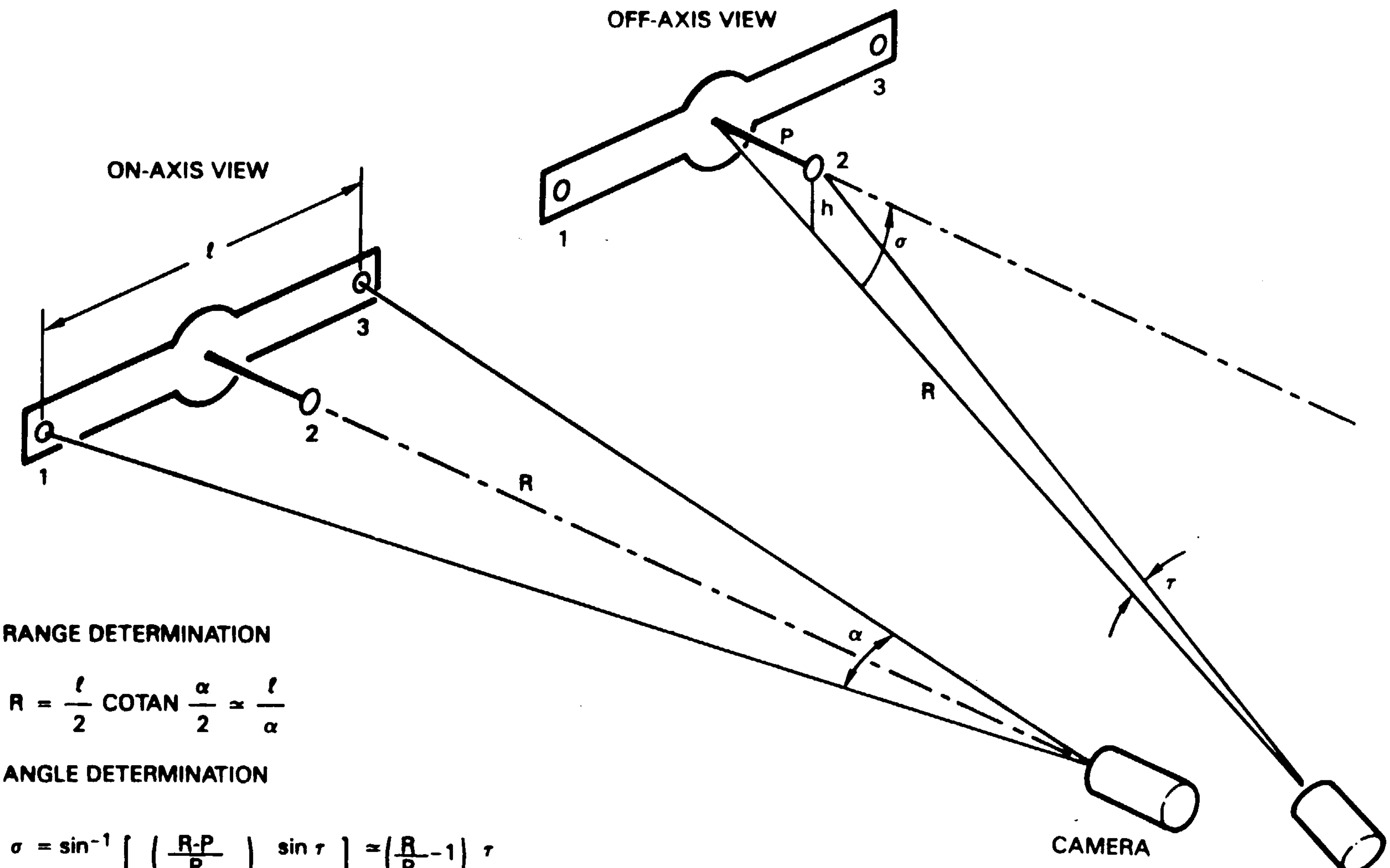
The geometry of range and angle determination by image data extraction from the video image of a T-shaped three-point target array carried by the target satellite is illustrated schematically in the chart. Range is determined on the basis of stadiametric measurement, using the subtended angle of the outer two reflecting targets 1 and 3 having a known separation ℓ. Bearing information is provided by the location of the centroid of targets 1 and 3 relative to the optical axis of the camera, which is assumed to be accurately aligned with the chaser body axis (x-axis). The off-axis view, on the right, illustrates the principle by which the misalignment angle σ can be detected, as a result of the apparent parallax of the tip of the central target pin (2) from the centroid of the outer two targets. In this view the angle deviation is shown in the vertical plane. Note that this parallax effect is the same as that being used in the manually controlled docking mode to detect the angular misalignment of the camera axis (and hence, the chaser body axis) with the docking face of the target satellite.

The pin parallax is a first order effect governed by the sine of the misalignment angle. It is a sensitive parameter at small excursions, but the sensitivity decreases as the angle approaches 90 degrees.

Stadiametric ranging based on the known distance ℓ is affected by the target body angle which reduces the apparent distance between the outer target reflectors, 1 and 3. This is a second order effect which only becomes significant for large off-axis angles. It can be corrected by taking the off-axis angle into account.

The method of extracting relative bearing and orientation angle data from the video target image is illustrated in the next chart.

RANGE AND ANGLE DETERMINATION FROM TV IMAGE



RANGE DETERMINATION

$$R = \frac{\ell}{2} \text{ COTAN } \frac{\alpha}{2} \simeq \frac{\ell}{\alpha}$$

ANGLE DETERMINATION

$$\sigma = \sin^{-1}\left[\left(\frac{R-P}{P}\right)\sin\tau\right] \simeq \left(\frac{R}{P}-1\right)\tau$$

TV IMAGE INFORMATION USED IN EXTRACTING RANGE AND ANGLE DATA FROM APPARENT RELATIVE POSITIONS OF THREE TARGET POINTS

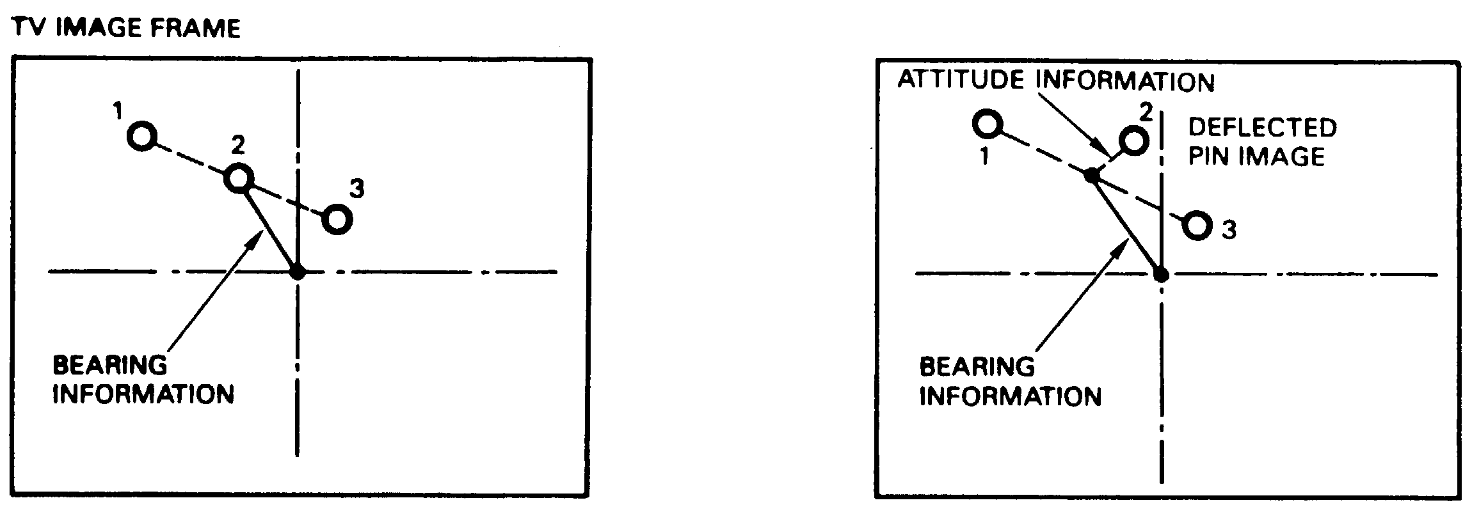
The chart illustrates the technique by which bearing and attitude information can be extracted from the relative location of the three reflector target images 1, 2 and 3 in the TV image frame.

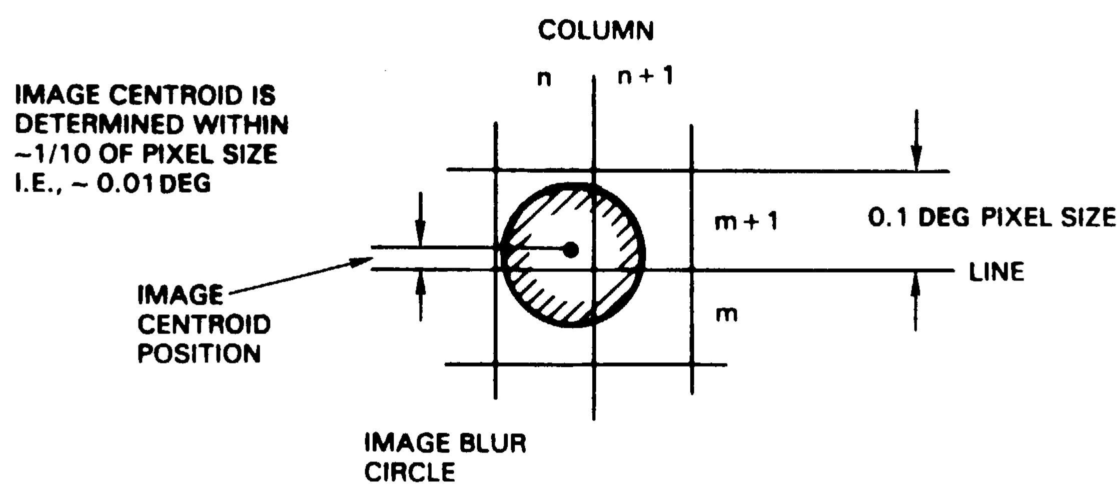
The left diagram shows the location and equidistant spacing of the end points 1 and 3 and their centroid from the camera optical axis, permitting the extraction of bearing angles (azimuth and elevation), as well as the roll misalignment.

The right diagram shows how the pin parallax (point 2 misalignment with respect to the centroid of segment 1-3) can be used to determine the pitch and yaw attitude angles in addition to bearing angles.

The diagram at the bottom shows that even with an image blur circle extending over several pixels in the image plane the centroid position of the blur circle can be determined with high accuracy. With a pixel size of about 0.1 degree on the docking camera, the image centroid should be measurable with an accuracy of about 0.01 degree, i.e., 1/10 of the pixel size. This resolution is consistent with a close range image interpretation accuracy greater than than required for high precision automated docking, i.e., ± 1 inch lateral, and ± 0.5 deg angular alignment, assuming a 3-point docking mechanism.

TV IMAGE DATA EXTRACTION FROM THREE TARGET POINTS





LASER DOCKING SENSOR (LDS)

A new Laser Docking Sensor (LDS) System currently being developed by McDonnell Douglas (MDSSC) under NASA/JSC contract is a potentially simpler, and highly accurate alternative for use in auto-rendezvous and docking. The chart describes the operating principle and some of the projected performance characteristics. The maximum acquisition range originally specified as about one nautical mile is currently being increased greatly (towards 100 nm) pending further definition of actual application requirements.

A five-point retroreflector array attached to the docking face of the target vehicle permits determination of relative range and bearing angles at large distances, and relative orientation angles at closer range, to permit 6-DOF control of the close approach and docking phase. Sensor signal processing yields the rates of change of all six relative motion coordinates.

Additional single-point retroreflectors mounted on other sides of the target vehicle facilitate acquisition by the LDS, if the docking face is not initially visible, and may even indicate the required maneuver direction by the chaser.

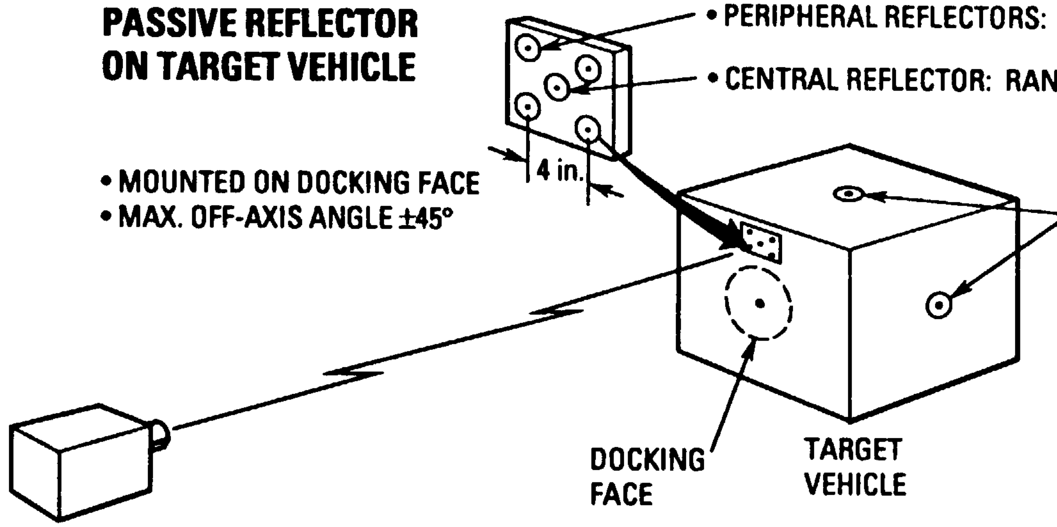
TRW Federal Systems Division
Space & Technology Group

Laser Docking Sensor (LDS)

PASSIVE REFLECTOR ON TARGET VEHICLE

- MOUNTED ON DOCKING FACE
- MAX. OFF-AXIS ANGLE ±45°

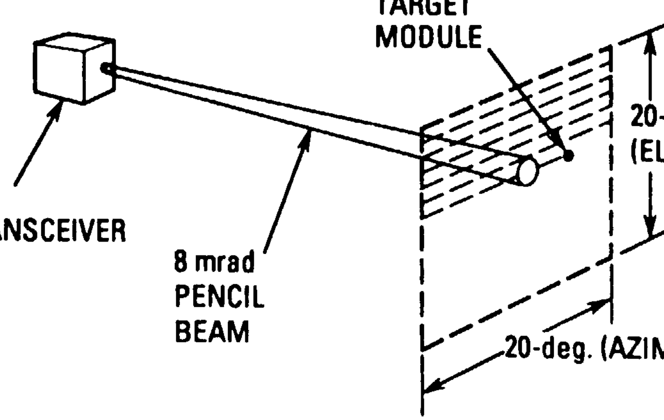
- PERIPHERAL REFLECTORS: REL. ORIENTATION ANGLES
- CENTRAL REFLECTOR: RANGE AND BEARING ANGLES



LDS TRANSCEIVER

- BROADBAND SOURCE 0.84 ... 0.93 MICRONS
- 20 x 20° TWO-AXIS TRACKING MIRROR
- PERFORMANCE: 1 km RANGE - 1 mm RESOLUTION
  3.6 km RANGE - 25 mm RESOLUTION
  RANGE ACCURACY: 2 in. @ R = 10 ft
  ANGLE ACCURACY: ~0.86 ARC min

TARGET ACQUISITION SEQUENCE



DATA FROM D. BRADBURY, MDSSC/SSD

REMOTELY CONTROLLED RENDEZVOUS AND DOCKING PROFILE WITH TARGET IN LOCAL VERTICAL/HORIZONTAL ATTITUDE

The chart depicts two nominal rendezvous and docking profiles where the docking sequence is controlled from the ground via TDRSS command and feedback communication links. The rendezvous phase starting at Point 1 with radar acquisition of the target is performed autonomously, supported by the rendezvous radar and GPS navigation data, with a midcourse correction occurring somewhere between Points 1 and 2 if necessary. The final approach phase to docking under manual control is initiated at Point 2, supported by radar data, video image and other telemetry data transmission to the ground.

Of the two approach profiles shown, the one approaching the target satellite from behind is generally preferred, since in this case, with both spacecraft flying in an easterly direction, the sun will illuminate the docking face of the target rather than being in the field of view of the camera during the critical close approach phase. That phase typically occurs in the later part of the daylight portion of the orbit, i.e., during the final 15 to 20 minutes before sunset.

In the auto-docking mode similar rendezvous and docking approach profiles will be flown if the target has a horizontal orientation, such as the one shown in the chart. If the video camera is used as the docking sensor, the same restriction on avoiding sunlight in the camera's field of view applies as in manually controlled docking. If a laser docking sensor is used instead, that restriction is not as binding. However, to permit manual control intervention or backup, based on using video information, the sun orientation constraint still must be observed.

For target orientations other than those shown here the approach profile, whether manual or automated, must be modified appropriately.

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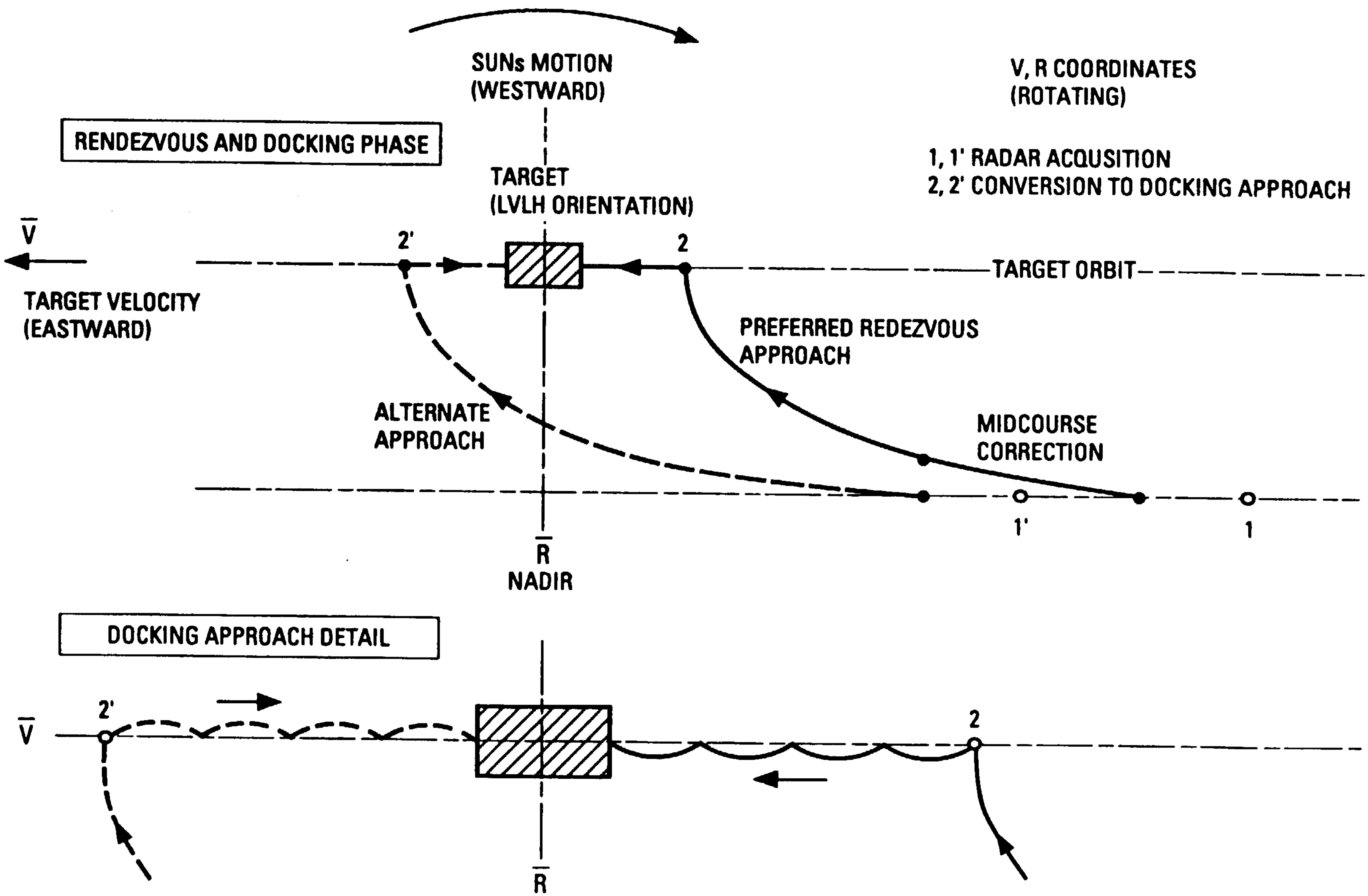
Remotely Controlled Rendezvous and Docking Profile with Target in Local Vertical/ Horizontal Attitude



C-3

POTENTIAL SUNLIGHT INTERFERENCE WITH DOCKING PHASE

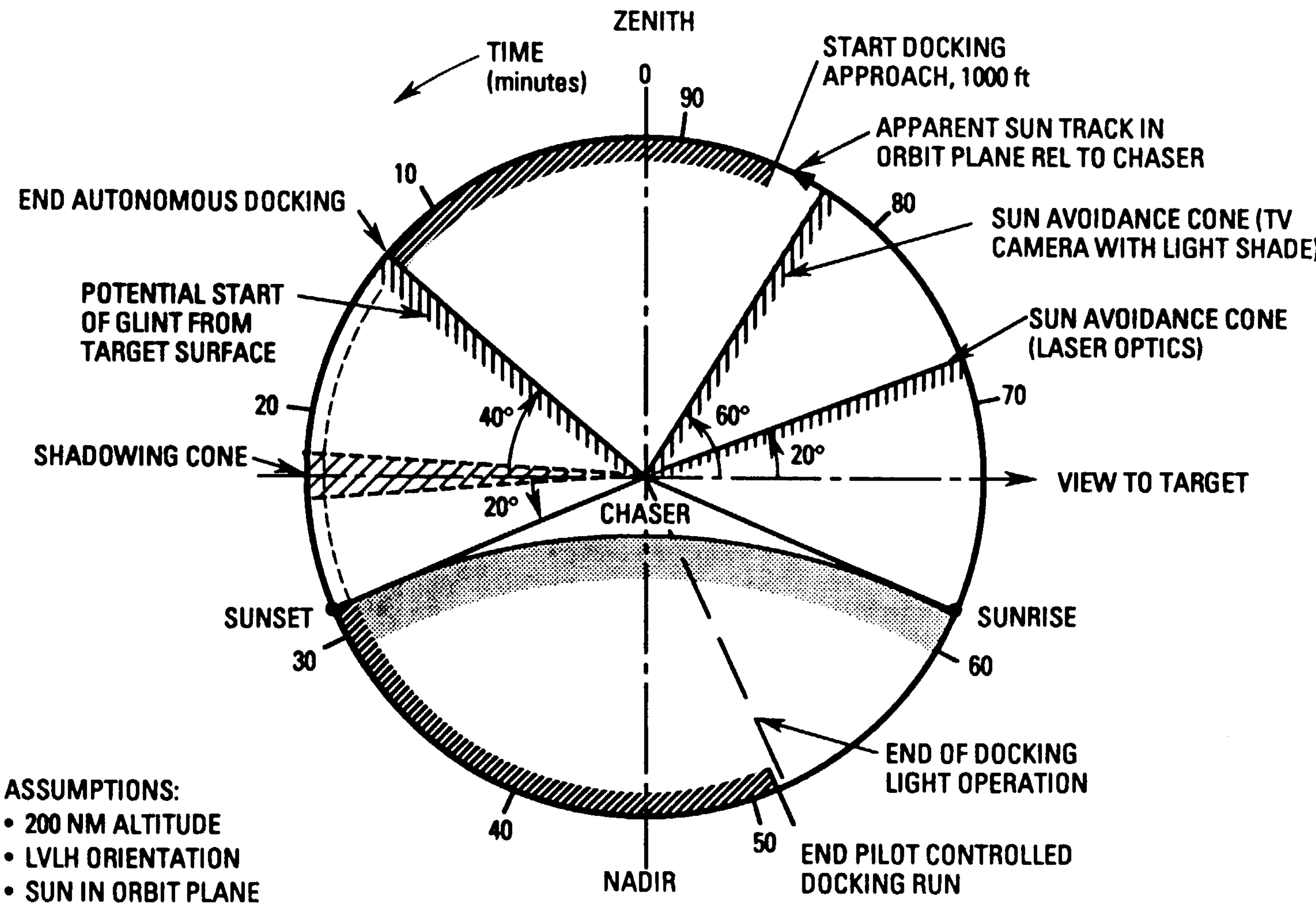
Potential sunlight interference with TV camera or laser docking sensor operation must be prevented by placing appropriate constraints on the docking approach timeline. The chart shows the apparent sun motion as seen by the chaser during its orbital revolution, assuming a "local vertical/local horizontal" (LVLH) body orientation. An approach from behind, rather than from in front of the target vehicle is selected, such that the setting sun is in the aft hemisphere of the chaser vehicle toward the end of the docking approach.

To avoid direct sunlight entry into the sensor optics the sun's orientation must remain outside a 60 to 90 degree (half angle) avoidance cone of the TV camera's field of view, and outside a 20 degree cone of that of the laser sensor after docking phase initiation. Therefore, the start of the terminal approach is deferred until the sun is within about 30 degrees of zenith. Auto-docking is estimated to be completed within 15 minutes, i.e., before the sun line enters a 40 degree cone in the aft hemisphere, where reflection from the target's docking face may cause glint in the TV camera's field of view.

In a human-operator controlled rendezvous/docking sequence, or in a supervised autonomous mission mode, the final docking phase, at distances of less than 100 ft, is deferred until after sunset and completed under docking light illumination. The nominal duration for using docking lights in darkness is 25 to 30 minutes, to keep power consumption within acceptable limits.

We note that due to seasonal changes the sun can be as much as 52 degrees out of the orbit plane (for a 28.5 degree orbit inclination), in which case the sun interference restrictions would be less severe.

Potential Sunlight Interference with Docking Phase



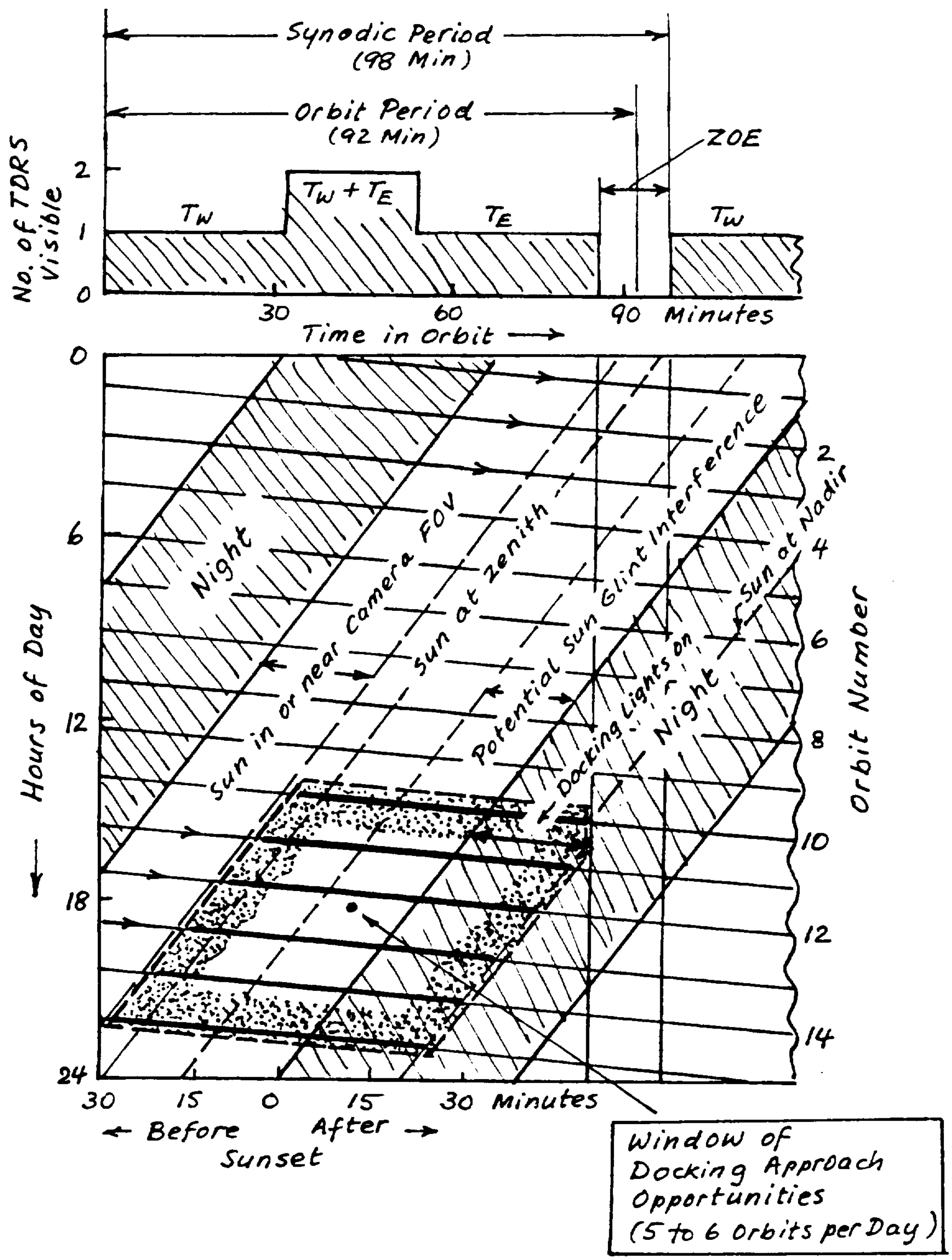
ASSUMPTIONS:
- 200 NM ALTITUDE
- LVLH ORIENTATION
- SUN IN ORBIT PLANE

TIME CONSTRAINTS IMPOSED BY LIMITS OF TDRSS COVERAGE AND POTENTIAL SUN INTERFERENCE

In addition to sun illumination and interference constraints (see preceding chart), those imposed by TDRSS coverage limits, i.e., 12 to 15 minutes of each orbital revolution (during passage of the "zone of exclusion" over the Indian Ocean), also must be applied to the mission timeline. The chart shows the combined target illumination, sun avoidance and TDRSS coverage constraints in a plot of time-in-orbit vs. time-of-day. Successive orbits are indicated by slanting lines, numbered 1 through 15. Inclined shaded strips indicate the eclipse part of each orbit. Dashed lines parallel to the sunrise and sunset boundaries indicate the time of the sun's zenith and nadir passage. Also shown are the boundaries of the 20 degree and 60 degree sun avoidance cones in the forward hemisphere, and the 40 degree glint avoidance cone in the aft hemisphere of the chaser vehicle centered on the two sensors' optical axes.

On top of the chart is a representative time history of the number of TDRS satellites (two, one or zero) visible at any time. Permissible docking opportunities between the rise time of the first and the set time of the second TDRS and the appropriate illumination limits are indicated by heavy line segments of several successive orbits. They are confined within shaded boundaries in the middle of the chart. For the conditions shown, only 5 to 6 orbits per day meet all TDRS viewing and sun interference avoidance constraints and thus, define a window of acceptable daily docking operations. With fully autonomous control the TDRSS communication constraints would be unnecessary, and docking approaches would be feasible in any of the 15 or 16 orbits per day.

TIME CONSTRAINTS IMPOSED BY LIMITS OF TDRSS COVERAGE AND POTENTIAL SUN INTERFERENCE



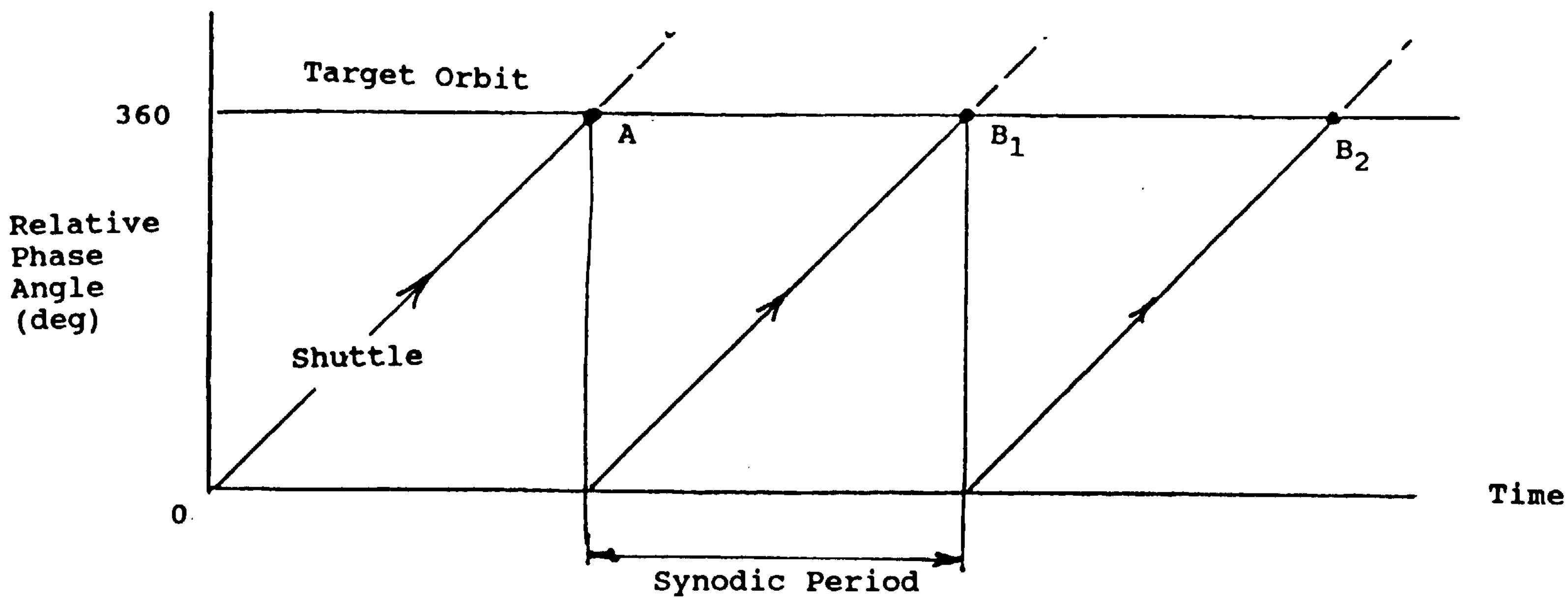
PHASE ANGLE CONSTRAINTS BETWEEN SHUTTLE AND TARGET ORBITS

The chart shows the relative phase angle vs time of the shuttle orbiter and the target vehicle based on the synodic period T_s between the two orbits. A chaser vehicle deployed from the orbiter to retrieve the target must perform its mission within these phase angle time constraints, e.g., by following a timeline that fits between points A and B_1, or B_1 and B_2 of the phase diagram, during one synodic period.

Remote satellite servicing missions require more time and therefore may have to extend over several synodic periods. These periods are inversely proportional to the difference of the respective orbit periods, and hence the altitude difference. For an altitude difference of 250 nm T_s is 15.5 hours, for 150 nm it is 28.5 hours, and for 50 nm 69.0 hours, assuming an orbiter altitude of 150 nm.

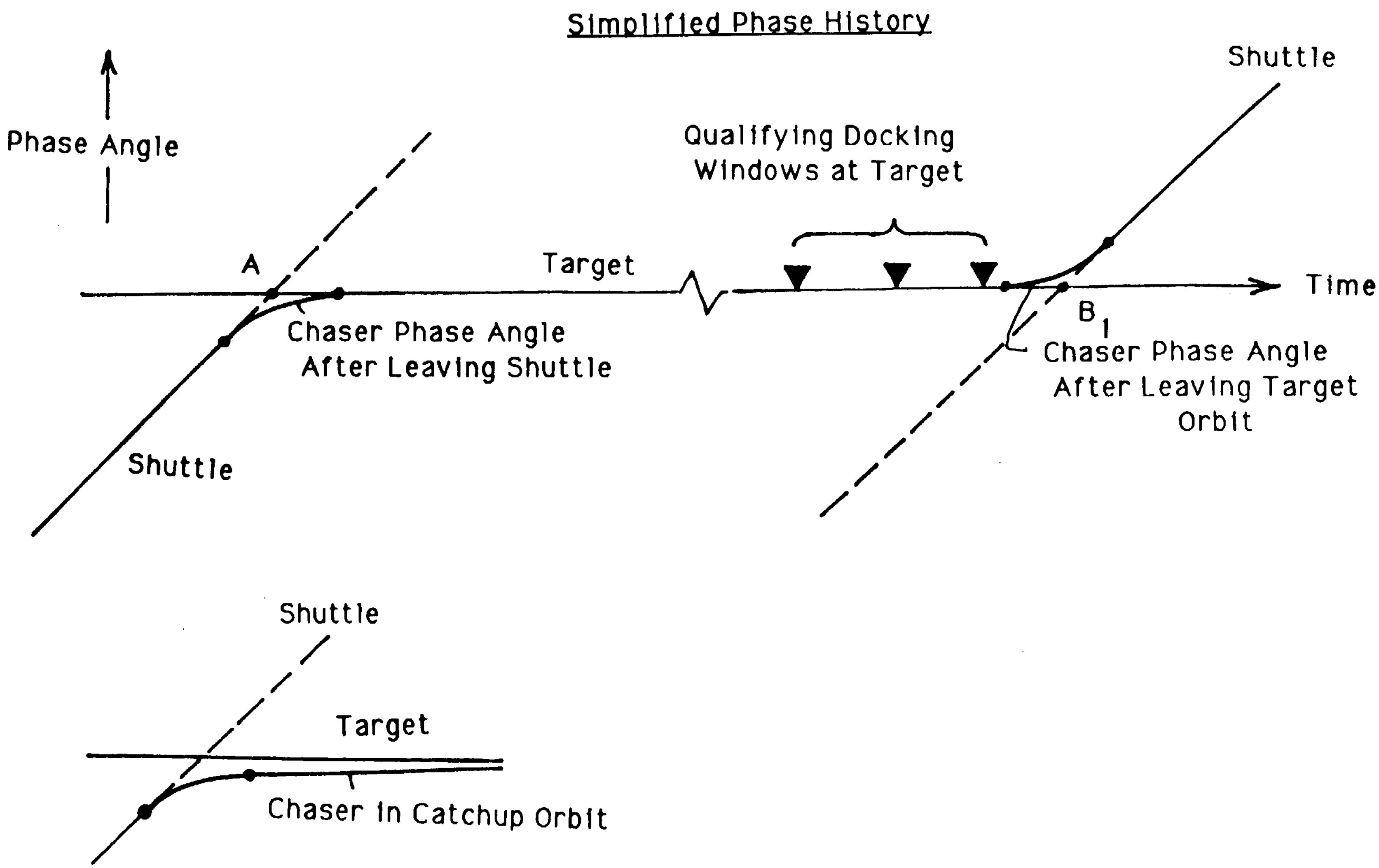
The next chart further illustrates this mission constraint, showing several docking windows at the target before the return opportunity to the orbiter at point B_1. Missing this opportunity would mean waiting for another full synodic period (which may be prohibitive under orbiter return-to-earth time constraints) or performing costly extra phase correction maneuvers.

PHASE ANGLE CONSTRAINTS BETWEEN SHUTTLE AND TARGET ORBITS



- Synodic Period $T_s = T_1 T_2/(T_2 - T_1)$
  where T_1 = shuttle orbit period, T_2 = target orbit period
- T_s = 28.5 hr for shuttle at 150 nmi and target at 300 nmi altitude (T_1 = 90.0 minutes, T_2 = 95.8 minutes)
- Mission to be performed within one synodic period to conserve power, either between A and B_1 or B_1 and B_2
- Time of shuttle main engine cutoff on ascent determines A and hence B_1, B_2, ...

TIME CONSTRAINTS OF SHUTTLE-TO-TARGET-ORBIT TRANSFER AND RETURN



REQUIREMENTS AND CONSTRAINTS SUMMARY

The facing table lists operational or functional requirements and constraints in several principal areas of concern, including navigation, guidance, control, R&D sensors, relay communication, from and to the ground station, target approach strategy and safety.

Some of the key issues and related requirements detail distinguish between remote control and autonomous control (with or without ground based supervision). Future full autonomy implies technology advances, needed in rendezvous and docking in planetary orbit as in the Mars exploration program where direct control or supervision from an Earth station is precluded, (Reference 6).

As an intermediate, evolutionary step supervised autonomous control will be used in earth orbital application, building up confidence in system performance capability and dependability, permitting man's involvement, if necessary, to assure successful mission completion.

REQUIREMENTS AND CONSTRAINTS SUMMARY

FUNCTIONAL REQUIREMENT	ISSUE	DETAIL
1. Navigation & Guidance	• Target Ephemeris	
	• Chaser State Vector	
	• Absolute Nav & Guidance	- To Rendezvous Point 1000 ft from Target
		- Error Ellipse $\pm$ 1 x 0.25 x 0.13 nm
	• Relative Nav & Guidance in Terminal Approach	- Acquisition by Radar at 4.5 nm
		- Final Approach Sensor
	• Terminal Approach	- Mode A: Remote Control
		- Mode B: Autonomous Control w/ or w/o Supervision
		- Pre-docking Alignment $\pm$ 1 Inch Lateral, $\pm$ 0.5^{o} Angular
		- Contact Speed < 0.1 ft/sec
2. Control	• Control Authority	- 4-DOF/6-DOF
	• Thruster Control Implementation	- 24 Vel. and Attitude Control Thrusters
		- Built in Thruster Selection
		- Redundant Modes
	• Attitude Hold and Auto-Stationkeeping Modes	- Permit Approach Interruption (Contingency Response)
	• Acceleration Constraints (Dynamics, Handling)	- Translation: > 0.05 to 0.1 ft/sec^2
		- Rotation: < 0.3 to 0.5 deg/sec^2

REQUIREMENTS AND CONSTRAINTS SUMMARY (CONTINUED)

3. Propellant Capacity	• Add Margin for Remote Control Inefficiency, Time Delay Effect • Allow for Phase Angle Correction and CAM Maneuvers	
4. Rendezvous/ Docking Sensor(s)	• TV with Image Extraction (Computer Vision), or LDS • High Sensor Resolution and Accuracy	- Avoidance of Sun Interference (Sun Avoidance Cone)
5. Ground Communication Via TDRSS	• In Remote Control Mode • In Supervised Autonmous Mode • TDRSS Accessibility Constraints • Restricted Number of R&D Opportunities Per Day (Due to TDRSS Non-Visibility)	- 12 to 15 Min Zone-of-Exclusion Passage Each Orbit - 1 Min Handover Gap Between TDRS-W and -E - Time Delay Effect Restricts Control Frequency (3 Sec Delay Corresp. to 0.1 CPS) - Windows Only During 5 to 6 Successive Orbits

REQUIREMENTS AND CONSTRAINTS SUMMARY (CONTINUED)

6.	Target Approach	• Nominally Preferred from Behind • Nearly Straight if Target in LVLH Orientation • Spiraling Approach if Target in Inertial Orientation or Slow Rotation (Relative to LVLH Coordinates)	- Avoids Sun Interference Close to Docking Phase - Approach Strategy Dictated by Sun Illumination and Interference
7.	Phase Angle Constraint	• Driven by Synodic Period • Phase Angle Correction Maneuvers If Non-Optimum Transfer	- ~ 30 Hrs for Delta H = 150 nm
8.	Safety and Collision Avoidance	• 2-Fault Tolerance Required in Manned Target Approach • Single-Fault Tolerance with Unmanned Target • CAM Provision Essential for Safety	- Nominal CAM Directions (Plus Large Dispersions) Specified in Four Regions Around Target - Excludes Later Inadvertent Target Contact

CONCLUSIONS

The data presented in this paper show the transition from an initially assumed, remotely controlled rendezvous and docking capability to one that would use fully autonomous techniques, with the rendezvous/docking sensor replacing the human control operator's response. Advantages include the avoidance of TDRSS relay communication, with its unavoidable inaccessibility periods, during passages through the "zone of exclusion"; the need for handover of coverage from one relay satellite to the other interrupting the control process; and the time delay effect on control performance. Supervised autonomy is an interim stage in this transition, still depending on the TDRSS relay, but otherwise speeding up the completion of the R&D mission phase.

Autonomous R&D will be essential in missions, such as planetary orbit rendezvous, e.g., in future Mars exploration, where the long rf transmission delay effectively rules out direct human operator control from Earth.

CONCLUSIONS

- SCENARIO ILLUSTRATIONS EXHIBIT KEY R&D REQUIREMENTS AND CONSTRAINTS
- AUTONOMOUS R&D (AR&D) CONTROL WILL EVOLVE IN TARGET RETRIEVAL AND SERVICING MISSIONS
- WILL ULTIMATELY REPLACE REMOTE, GROUND-BASED CONTROL
- SUPERVISED AR&D IS INTERIM STAGE, WITH HUMAN OPERATOR MONITORING, AND INTERVENTION IF NECESSARY
- FULL AUTONOMY AVOIDS LIMITS ON DAILY R&D OPPORTUNITIES DUE TO COMMUNICATION LINK (TDRSS VISIBILITY) CONSTRAINT
- AR&D FASTER, MORE PRECISE AND MORE FUEL EFFICIENT THAN REMOTE CONTROL
- SUN ILLUMINATION AND INTERFERENCE PRIMARILY AFFECTS REMOTE CONTROL VIA TV FEEDBACK

REFERENCES

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3. "Development of an Autonomous Video Rendezvous and Docking System", Phase I, II, and III, by J. C. Tietz and J. H. Kelley, Martin Marietta, Contract NAS8-34679, 1982, 1983, and 1984

4. "Automatic Rendezvous and Docking: A Parametric Study", by R. W. Dabney, NASA Technical Paper No. 2314, May 1984

5. "Development of a Video-Based Automatic Rendezvous and Docking System", by R. T. Howard and R. W. Dabney, NASA/MSFC, Paper MS89-231, SME Conference on Robots in Aerospace Manufacturing, Irvine, CA., February 1989

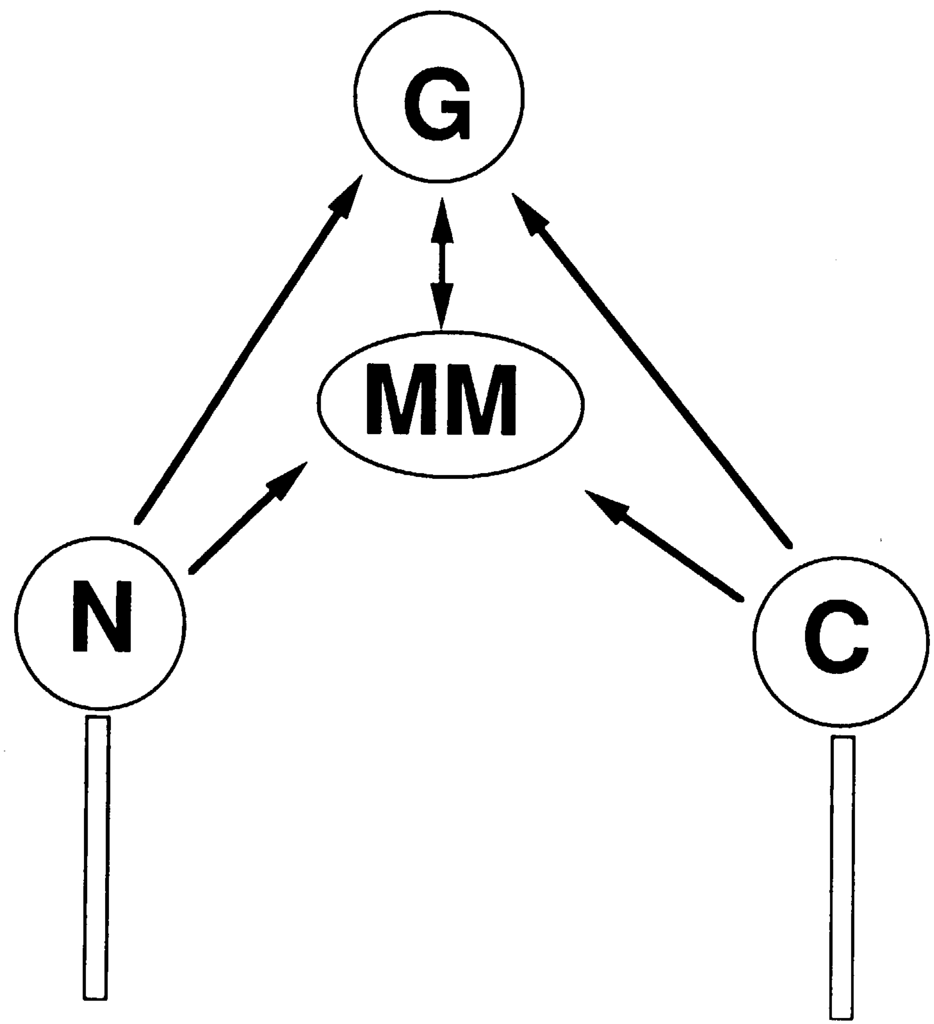
6. "Pathfinder Autonomous Rendezvous & Docking Activities at JSC", Briefing by Stephen Lamkin, Johnson Space Center, January 23, 1989

Operational and System Dependent Considerations and Constraints for Designing an Autonomous Rendezvous or Docking System.

Christian K. Meyer
August 15-16,1990
ARD Conference
Rockwell Space Operations Company

In any Rendezvous System the limitations of the navigation and control systems will constrain the ability of the system as a whole. The Mission management and Guidance Functions will need to adapt, update and priority based upon the limits of navigation and control.

Navigation and Control Limitations Will Effect Guidance and Mission Management Options



In this presentations the standard definition of control is extended to include all vehicle systems. These include power, propulsion, thermal management and communication and data handling. Thus, in this definition control limitations are analogous to Hardware limitation. In an autonomous rendezvous system, hardware limits on both vehicle, the target and chaser, effect the overall system.

Clearly the limitations of the navigation system will effect the ability of the autonomous rendezvous system to perform its assigned task.

These limits are the reasons we have flight controllers for todays space vehicles. For some vehicles most of the nominal operations are completed by flight controllers through commands to the spacecraft. As the level of spacecraft independence increases, more and more of the standard housekeeping duties are completed by onboard systems, and the role of the ground controller concentrates on off nominal and payload specific operations.

The scope of autonomy will also be a factor of the phase of the mission. Are maneuvers separated by days and hours, or minutes and seconds.

Navigation and Control Limitations Will Effect Guidance and Mission Management Options

Limitations Exist on System as a Whole

- Vehicle (Hardware) Constraints

  Chaser
  Target

- Knowledge of Vehicle States

Phase of mission determines importance of these limitations - MNVR's seperated by days & hours or minutes & seconds

Autonomous control will reside within the functions of the mission manager. The guidance system will act primarily as a trajectory specialist.

At a base level, the inputs to the mission manager and guidance are: a set of prioritized mission objectives, a propellant budget, a time budget, and a navigation state.

The output would consist of a safe transfer between two points. The end conditions can either be intercept - either with desired conditions, or acceptable levels: IF a system failure constraints the ability of the vehicle to finely control, does the guidance algorithm need to be updated in order prevent requests for unachieveable goals.

The output may also consist of abort trajectories. This can mean the end of the rendezvous, if so what must I do to preserve the rest of the mission. Aborts can also apply to delays in the profile: several rev delays, as well as short term proximity operation stationkeeping. An example would be an unsuccessful docking attempt due to docking hardware failure. This would be followed by a standoff between vehicle at short range, while either ground controllers or on-board software troubleshoots the docking hardware. This type of situation would also apply to the unexpected tumbling of a spacecraft due to plume impingement, or attitude control system failure.

Mission Manager Provides Decision Making Capabilities
Guidance System Trajectory Specialist

Inputs

- Prioritized Mission Objectives
- Propellent Budget
- Time Budget
- Navigation State

Output

- Intercept - Desired Conditions
  Acceptable Conditions
- Abort Trajectories - End RNDZ - What is rest of mission?
  Null for Several Revs - coelliptic, "football"
  Null for Short Term - r<300m - V Stationkeep

The vehicle, or hardware, constraints fall in to four categories. The first is plume impingement, primarily from the chaser vehicle onto the target vehicle. The can result in contamination to science and optics, or overpressure - unacceptable plume induced torques resulting in physical damage or loss of attitude control. These concerns can result in requirements on close in relative motion. Fortunately, most the profiles (orthogonal braking, glideslope) that result in the lowest plume loads, also require smaller levels of fuel.

Limitations on Sensors will place limits on how you design the rendezvous profile. The relative navigation phase of the rendezvous is achievable with today's sensor technology and application. The ability to perform autonomous inertial navigation is more of a question, especially at remote locations such as Mars.

Even the fairly robust navigation sensors that exist today can place limits on the nearfield rendezvous profile. Line of sight limitations exist, they cannot be used at large phase angles, and fields of view are limited by planetary and solar horizons (geometry of more than just the target must be considered). Orbital lighting must also be considered. Startrackers place some restrictions on relative motion for data passes. A important consideration for sensors is redundancy, and the desire to avoid single point failures. This also applies to independent orbiting and ground sensors as well. Any single point system must be treated as nonexistent, or loss of the system is a non-credible failure, in the design of the rendezvous profile. The single point Ku-Radar on the Space Shuttle is a classic example, the rendezvous profile must be designed to use only the startrackers. Finally, other uses of sensors must be considered - such as startrackers for IMU alignment's and Radar antennae for communication.

Vehicle (Hardware) Constraints Impact Rendezvous Profile

Plume Impingement Concerns (contamination, overpressure) can determine final approach geometry glideslope approach or orthoganal braking

Sensors - Profile May be limited by performance specifications, target size

Range Limitations
Line of Sight Limitations - cannot be used at large phase angles
Geometry Requirements - relative angular change for Startrackers
Redundancy - single string systems are undesireable
Other Uses - IMU alignment

Attitude requirements on the chaser vehicle can also introduce limitations. Thermal condition may be required for science, payloads or docking hardware. The direction of propulsive vents and water dumps must be controlled to minimize perturbations. Combined with the physical location of sensors, this can put the vehicle in attitudes that are not conducive to the use of the sensors.

Propulsion constraints will also limit rendezvous capabilities. Jet failures, and the level of redundancy, may prevent certain translational axis from being used, requiring attitude mnvr's to use other axis to achieve required delta-V's. Even if redundancy exists it may be desirable to inhibit use of thrusters until flight critical phases such as entry or proximity operations.

Partial loss of fuel supply does not necessarily mean loss of mission, but does mean that previously planned profiles may not be acceptable. Does the mission manager reprioritize guidance priorities, maximizing propellent to the exclusion of other variables.

Depending on the overall requirements that went into the design of the vehicle, jets can be located such that motion is quite coupled. Both rotation and translational firings can couple into undesirable translation in other axes. In addition, attitude firings can add to or decrease the orbital energy. Since effects of these attitude firings may fall beneath the threshold of the IMU's, this energy must be predicted and modelled by the guidance system.

Vehicle (Hardware) Constraints Impact Rendezvous Profile

Attitude Requirements

Thermal Conditioning of Science, Payloads, Docking Hardware
Propulsive Vents, Water Dumps
Physical location of Sensors

Propulsion System Limitations

Jet Failures - redundancy - will you reserve operation for critical flight phase (proximity operations, deorbit, entry)

Fuel Limits - If failures limit propellent supply - does MM reprioritize guidance criteria

Cross Coupling - Rotation > Translation
Translation > Translation
Attitude Hold > Translation

Expected Attitude Profile and Undesired Maneuver Effects Must Be Predicted and Modelled for an Optimal Trajectory.

Errors in state knowledge will obviously effect the capabilities of an ARD. The severity of the effects is a function of mission location, sensor capabilities and overall mission design. Mission location will determine the ability and frequency of independent updates to the GN & C system. Error comes from initialization errors, relative navigation sensor errors and errors in propagation (modelling errors, attitude firings, IMU bias and noise). A significant factor can be the time of propagation since the last update. For the STS, the largest errors in propagated state often come from IMU align attitude, and water dump attitude mnvr's. They fall below the threshold of the IMU's, and it requires several orbits of TDRS and C-Band tracking to solve for the effects. In the time it takes to solve for these effects, the certainty of the Orbiter's position decreases. For missions in Lunar or Mars orbits, these effects must be minimized, since the time between inertial NAV updates is likely to be dependent on a system that is not as capable as that used for the STS.

This uncertainty in the STS location is the largest dispersion that must be accounted for at the transition point between inertial navigation and relative navigation. The limits of the onboard sensors make this handover region very tenuous.

Error in Knowledge of State Impacts Profile

Severity Controlled By

- Location of ARD Mission - LEO, GEO, Moon, Mars
- Capabilities of Sensor
- Design of Mission - frequency of independent checks and updates

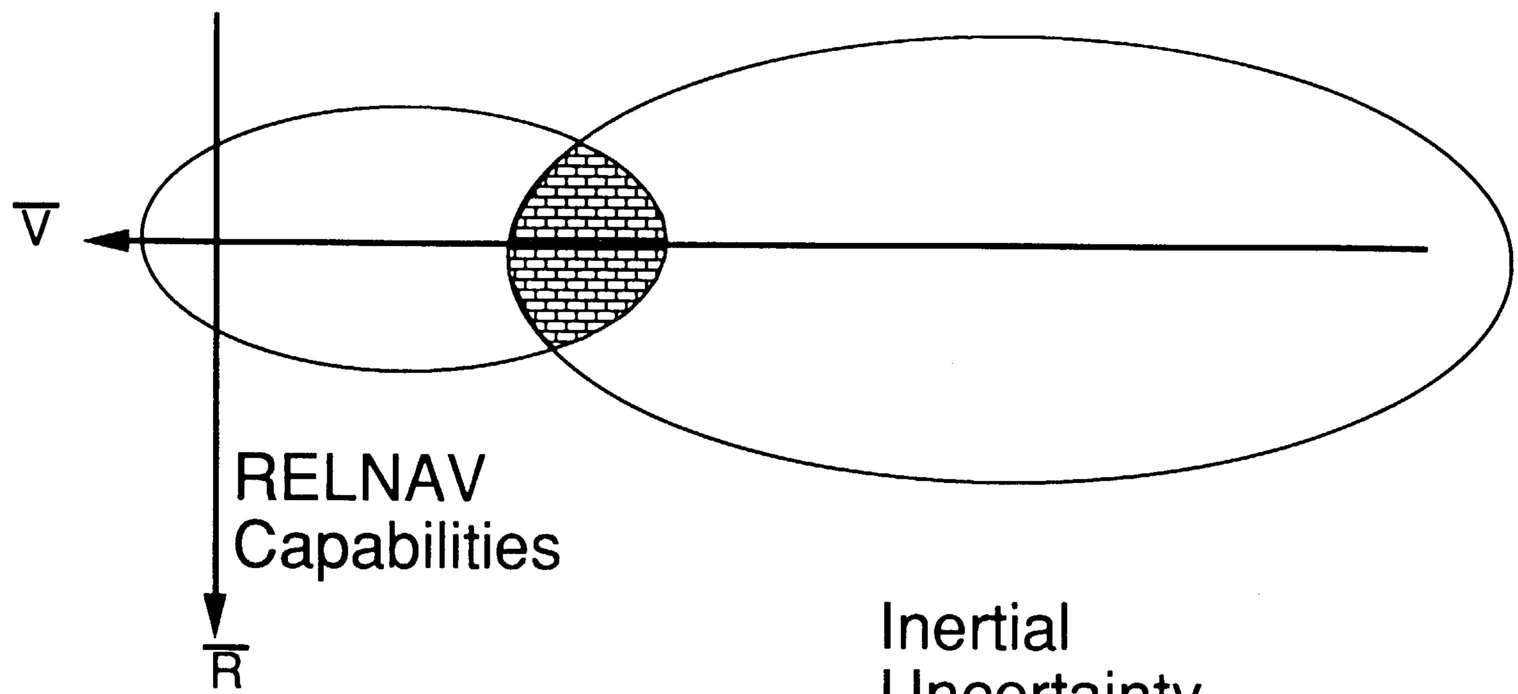
Error Sources

Startup (SEED) - Bias and Noise of initial Ground or Spaceborne System

Relative Navigation - Bias and Noise of Onboard Sensors

Propagation -
- IMU/Accelerometer - Bias, Noise
- Unmodelled Accelerations - changing environment, attitude firing effects < threshold of Accelerometers
- Time Since Last Update - duration of error propagation

Error in Knowledge of State Impacts Profile



Must have a stable transition between Inertial NAV and Relative NAV. Provide Enough Accuracy for automatic system takeover with relative position and energy within budget.

SUMMARY:

The limits within the navigation and control systems will determine the ability of system to perform in an autonomous fashion, limiting tools available, and relative motion that is allowed.

Autonomy is vital to future missions, starting with logistical supply to Space Station Freedom, and progressing with Lunar and Mars operations. At a program level, the physical limitations must be reviewed. The level of autonomous decisions, all vehicle systems, selected systems, payload control, up to and including programmatic decisions. As the scope of future missions grows, so must the ability of independent systems to control them. Rigorous testing will not always be possible, however the envelope of few complex spacecraft are known prior to flight, so systems must have the capability to learn and expand.

SUMMARY

Limitations of Navigation and Control Must be Addressed in the Design of Guidance and Mission Management Subsystems

Can Force Requirements On Relative Motion Profiles - Near Field RNDZ & Proximity Operation

Can Limit Tools Available to Complete the Mission

Limits of System Will Determine Level of Autonomy That is Acceptable

System Architecture for Autonomous Rendezvous and Docking

David P. Dannemiller
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This presentation addresses some of the factors which affect system architecture for autonomous rendezvous and docking systems.

The author's experience is in the STS program. STS examples are used throughout.

Table of Contents

Mission Phases

Dividing the mission into phases decomposes the problem into more manageable segments.

Mission Phase Definition is Useful

- Logical division of models, GN&C, etc
- Allows focus to shift as needed
- Some phase characteristics are generic and some program specific

Mission Phases (cont.)

Many of the mission phase characteristics are generic. Modeling fidelity increases as the vehicles get closer.

Reaction time decreases as the vehicles get closer. Prior to launch, the system may have lots of time to "think" and plan. During docking, decisions must be immediate.

Generic Phase Characteristics

Mission Phase	Modeling	Navigation	Reaction Time
pre rndz	3 DOF	inertial	hours - months
far field rndz	3 DOF	inertial	hours - days
near field rndz	3 DOF	relative	minutes
proximity ops	6 DOF rigid plume	relative with att	seconds
docking	6 DOF non-rigid plume dock mech geom contact dyn	between docking ports	immediate

Mission Phases (cont)

This table shows sample characteristics for the STS. These characteristics should not be extrapolated to other programs without careful thought.

Responsibility for decisions and computations is divided between the ground and onboard elements. For rendezvous and "docking", the "prime" responsibility moves from ground to onboard as the rendezvous progresses.

Specific STS capabilities and limitations determine the range were each phase starts. For example, at 1000 ft, plume impingement is a factor and the crew has taken manual control. These define the beginning of proximity operations.

The trajectory design problem is standardized to different levels for each phase. During the far field rendezvous phase, mission specific objectives (such as deploy of other payloads) cause a unique design for each mission.

Sample STS Phase Characteristics

Mission Phase	Prime	Start range	Trajectory Design
pre rndz		(launch)	std/tailored
far field rndz	ground	thousands NMI	mission specific
near field rndz	↓ ↑	40-100 NMI	canned
proximity ops		1000 ft	std/tailored
docking	onboard		payload specific

Mission classes

self explanatory

Mission Classes

- Upcoming programs span broad range
  - STS
  - STS-C
  - OMV
  - Satellite servicer
  - EVA retriever
  - SEI

Mission Classes (cont)

Automation of the rendezvous and docking problem is simplified for cooperative targets. These targets are controllable, have a well controlled docking environment, and may cooperate with the chaser sensor system.

Life cycle costs will encourage automation for programs which have many missions.

Automation is required for programs which have significant communication delay between the flight vehicles and a human operator. A human operator may have a role during early mission phases where the reaction time is longer.

Mission criticality will determine how robust the system must be. Critical missions will require more redundancy and/or autonomy to achieve this robustness.

Mission Characteristics

- Mission characteristics determine desired level of automation
  - cooperative vs non-coop target
  - one time vs continuing operations
  - communication delay/reliability
  - mission criticality

Automatic vs Autonomous

The level of automation for a system varies form none (totally manual) to automatic to autonomous.

Definition of Automation Levels

- Manual - worked by hand

- Automatic - made so that certain parts act in a desired manner at the proper time

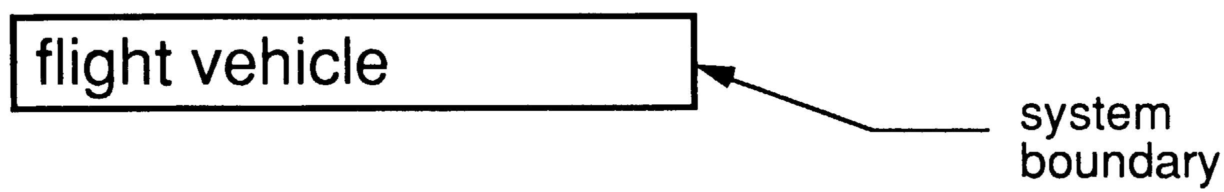
- Autonomous - having the right or power of self-government (the making of policy (a definite course or method of action selected to guide and determine present and future decisions))

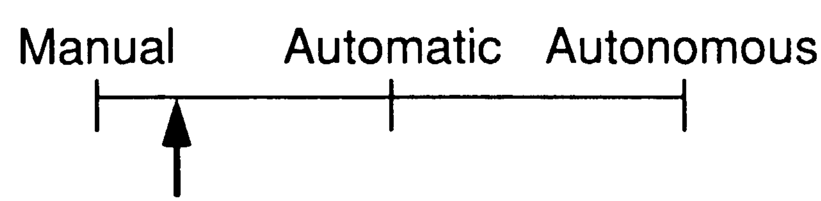
Ref: The Merriam-Webster Dictionary

Automatic vs Automation (cont)

The level of automation of a system depends on where the system boundary is drawn. For STS rendezvous, if the boundary includes only the flight vehicle, the system is not very automated.

Level of Auto vs System Boundary





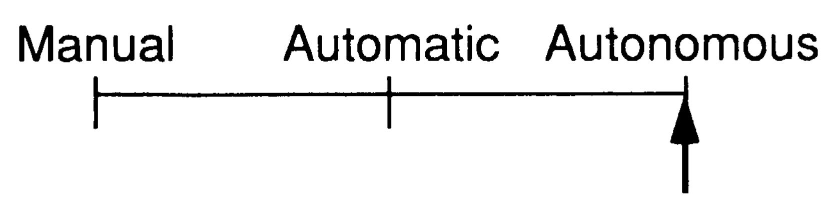
Automatic vs Automation (cont)

The system automation increases as more of the elements listed are included in the system boundary.

Level of Auto vs System Boundary

flight vehicle
flight crew
MCC
manufacturers
NASA management

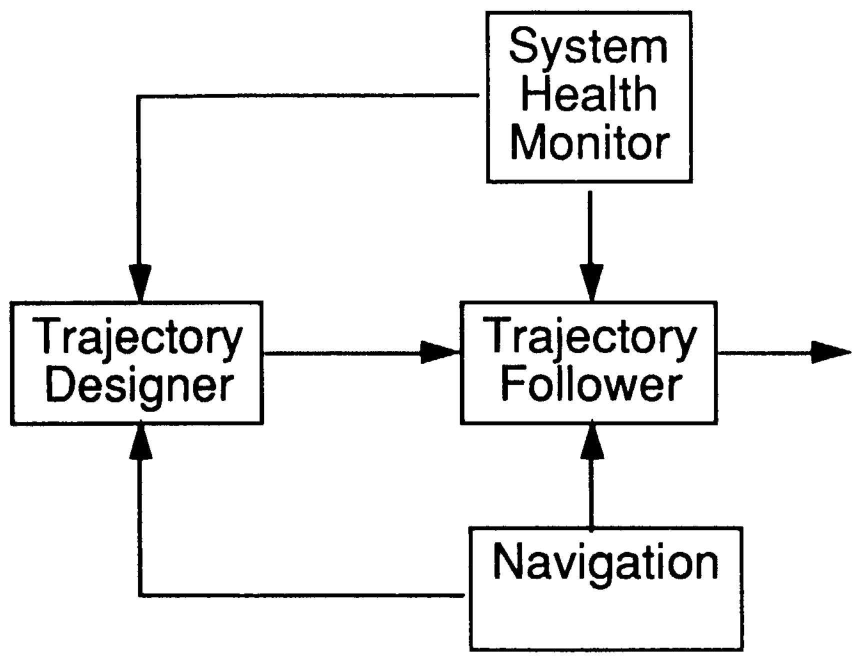
system boundary



System Architecture

self explanatory

System Architecture



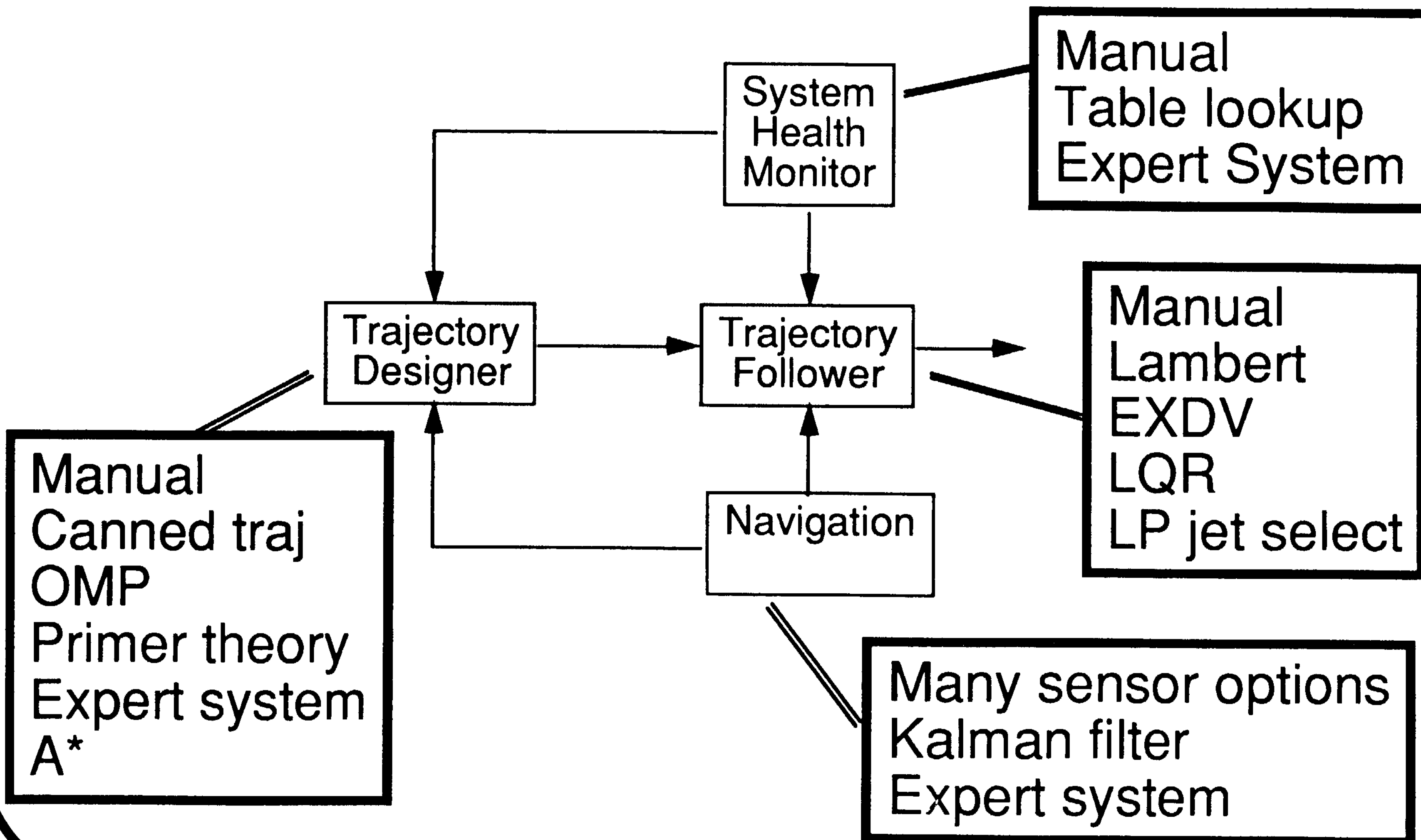
System Architecture (cont)

This is a partial list of techniques applicable to the blocks within the system. The characteristics of different missions classes and mission phases will lead to many system designs. Standards can and should be established where possible.

The role of man should be carefully considered. Where a combined manual and automated design is needed, the transition from human monitoring (with automated system operation) to total manual control must be well designed. Where possible, different levels of manual control should be provided so the human need take only as much control as required.

Expert systems and other artificial intelligence techniques will definitely have a role in autonomous systems. However, many of the trajectory design and control functions are well defined. Numerical solutions are preferred in these cases.

Applicable Techniques



Summary

- Address all mission phases
- Different programs require different levels of automation
- "Totally" autonomous flight element not always needed
- Most pieces has been started. Some more mature than others

AUTOMATION ISSUES FOR RENDEZVOUS AND PROXIMITY OPERATIONS

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PRESENTED AT

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

August 15-16, 1990

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lea/jani/r&d_notes/ar&d90

PRESENTATION FORMAT

- INTRODUCTION
- OBJECTIVES
- RENDEZVOUS AND PROXIMITY OPERATIONS SCENARIO
- AUTOMATION AREAS
- ISSUES/CONCERNS
- CURRENT AUTOMATION ACTIVITIES IN SOFTWARE TECHNOLOGY LABORATORY
- SUMMARY

INTRODUCTION

- FUTURE SPACE OPERATIONS REQUIREMENTS
  - AUTONOMOUS CONTROL
  - INTELLIGENT SENSORS
  - DIAGNOSIS AND RECONFIGURATION SYSTEMS
  - DECISION SUPPORT SYSTEMS

- MISSION SUCCESS WILL DEPEND ON
  - THE DEGREE OF AUTOMATION
  - RESOLUTION OF PROBLEMS OF AUTONOMOUS OPERATIONS
  - DEVELOPMENT OF ADAPTIBLE SYSTEMS
  - DEVELOPMENT OF INTELLIGENT SW/HW SYSTEMS THAT CAN FUNCTION INDEPENDENT OF HUMAN INTERACTION FOR AT LEAST SHORT TIME INTERVALS

OBJECTIVES

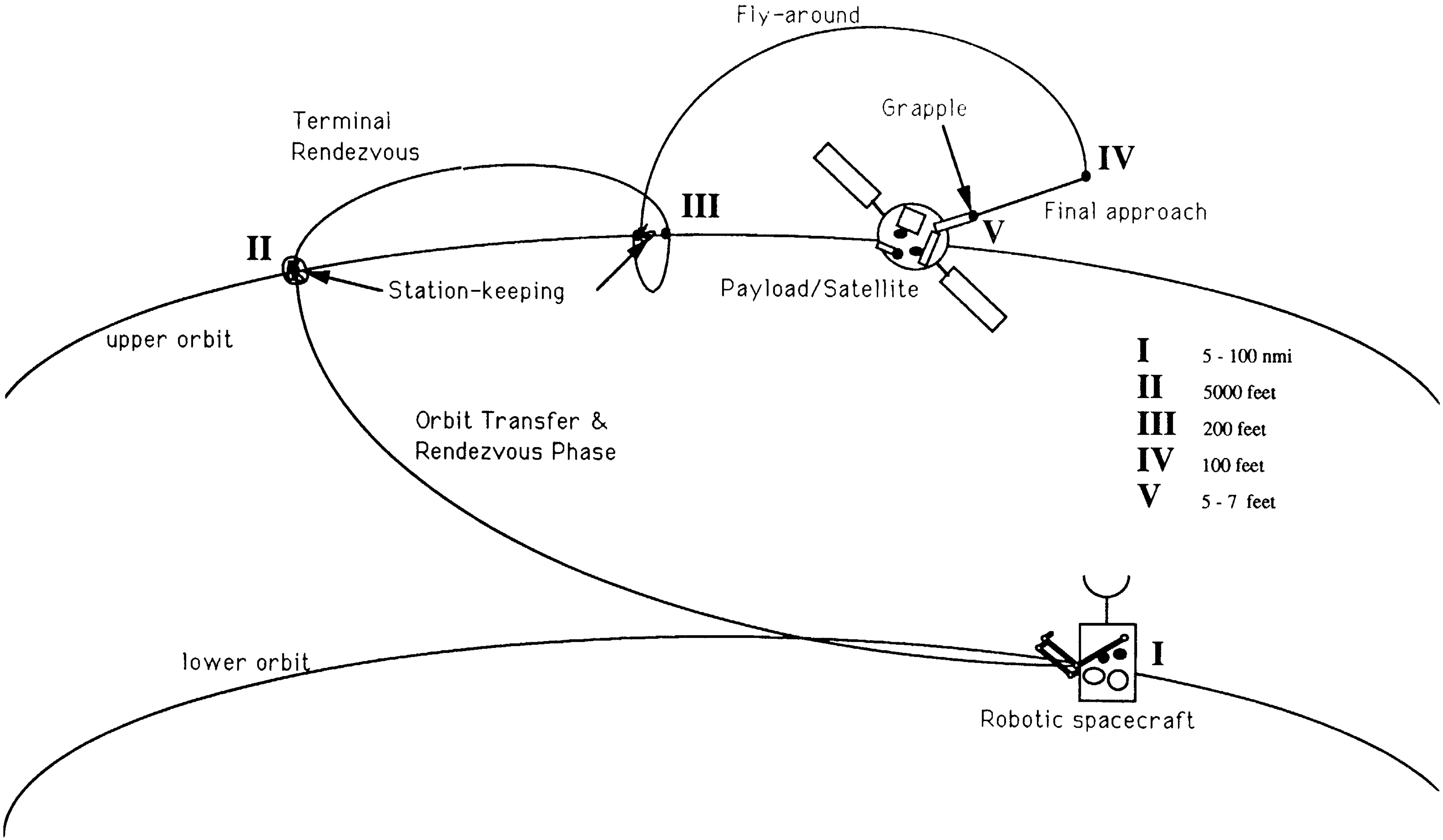
- DISCUSS THE RENDEZVOUS AND PROXIMITY OPERATIONS AREAS WHERE AUTONOMOUS OPERATIONS ARE FEASIBLE, ADVANTAGEOUS AND ENHANCE THE MISSION SUCCESS

- IDENTIFY THE ISSUES AND CONCERNS THAT NEED TO BE RESOLVED FOR SUCH AUTONOMOUS SPACE OPERATIONS

- DESCRIBE THE CURRENT ACTIVITIES IN THE SOFTWARE TECHNOLOGY LABORATORY THAT DIRECTLY SUPPORT AUTONOMOUS OPERATIONS

RENDEZVOUS AND PROXIMITY OPERATIONS SCENARIO

- TWO VEHICLES ONE ACTIVE AND ONE PASSIVE AT A DISTANCE OF 10+ MILES
- ACTIVE VEHICLE PERFORMS ALL MANEUVERS ACCORDING TO A FLIGHT PLAN
- PASSIVE VEHICLE HOLDS DESIRED ATTITUDE
  - IF POSSIBLE, CONTINUOUSLY MONITORS THE PERFORMANCE OF ACTIVE VEHICLE (e.g. A MANNED BASE MUST MONITOR ALL ACTIVITIES AS A PASSIVE VEHICLE)
- PROXIMITY OPERATIONS ZONE IS WITHIN 5000 FEET OF A PASSIVE VEHICLE OR A MANNED BASE



MISSION SCENARIO

AUTOMATION AREAS

- TRAJECTORY PLANNING
  - NOMINAL AS WELL AS ALTERNATE FLIGHT PLANS
  - DETERMINATION OF BURN SEQUENCE e.g. TIME-LINE
  - COMPUTATION OF DELTA-V's, TIME OF IGNITION, VEHICLE ATTITUDE DURING BURN
- GUIDANCE AND NAVIGATION DURING TRANSFER ORBIT
  - MONITORS THE DELTA-V EXECUTION AND SETS THE CUT-OFF TIME
  - COMPUTES CURRENT STATE INFORMATION FROM SENSOR DATA (inertial and relative position, inertial and LVLH attitude)
- TRAJECTORY CONTROL OF AN ACTIVE VEHICLE
  - TRANSLATIONAL CONTROL (execution of delta-v)
  - ROTATIONAL CONTROL (maintenance of pointing vector)
- INTELLIGENT SENSORS : MONITORING AND TRAFFIC MANAGEMENT BY MANNED BASE WILL BE ENHANCED SIGNIFICANTLY

ISSUES AND CONCERNS

- TRAJECTORY PLANNING
  - FACTORING INFORMATION SUCH AS SIZE AND SHAPE OF DESIGNATED APPROACH CORRIDOR TO A PASSIVE VEHICLE OR MANNED VEHICLE SUCH AS SPACE STATION FREEDOM
  - DEVELOPMENT OF DESIGN REFERENCE MISSIONS
    - NOMINAL AS WELL AS CONTINGENCY MISSIONS
    - MISSION GOALS, MISSION SCENARIO AND OPERATIONS INTERFACES ARE INCLUDED
    - MAXIMUM DEVIATION ENVELOPE FOR AUTONOMOUS VEHICLES
  - ADAPTING TO APPROXIMATE CONDITIONS OR GOALS
- SENSOR CAPABILITIES REQUIRED FOR AUTONOMOUS OPERATIONS ; DATA FUSION METHODS WHEN SEVERAL SENSORS ARE PROVIDING MEASUREMENTS ; METHODS TO HANDLE IMPRECISE MEASUREMENTS
- OPERATIONS INVOLVING MANNED AND UNMANNED /AUTONOMOUS VEHICLES
  - CAPABILITY OF OVERRIDING THE AUTONOMOUS OPERATIONS; CREW TRAINING FOR REMOTELY CONTROLLING AN AUTONOMOUS VEHICLE IF NECESSARY
  - HEALTH AND STATUS MONITORING CAPABILITIES ONBOARD THE AUTONOMOUS SPACECRAFT

CURRENT AUTOMATION ACTIVITIES IN SOFTWARE TECHNOLOGY LABORATORY / NASA / JSC

- PROXOMITY OPERATIONS

  - DEVELOPED CONTROLLER BASED ON FUZZY SETS FOR TRANSLATIONAL CONTROL OF AN ACTIVE VEHICLE IN APPROACH, STATIONKEEPING AND FLYAROUND OF A TARGET VEHICLE

  - DEVELOPED AN ATTITUDE CONTROL CAPABILITY BASED ON A FUZZY PHASE PLANE APPROACH FOR AN ACTIVE VEHICLE

  - STUDYING AUTOMATED METHODS OF MISSION PLANNING THAT CAN DEAL WITH CONTINGENCIES AS WELL AS NOMINAL PLANS

- RENDEZVOUS

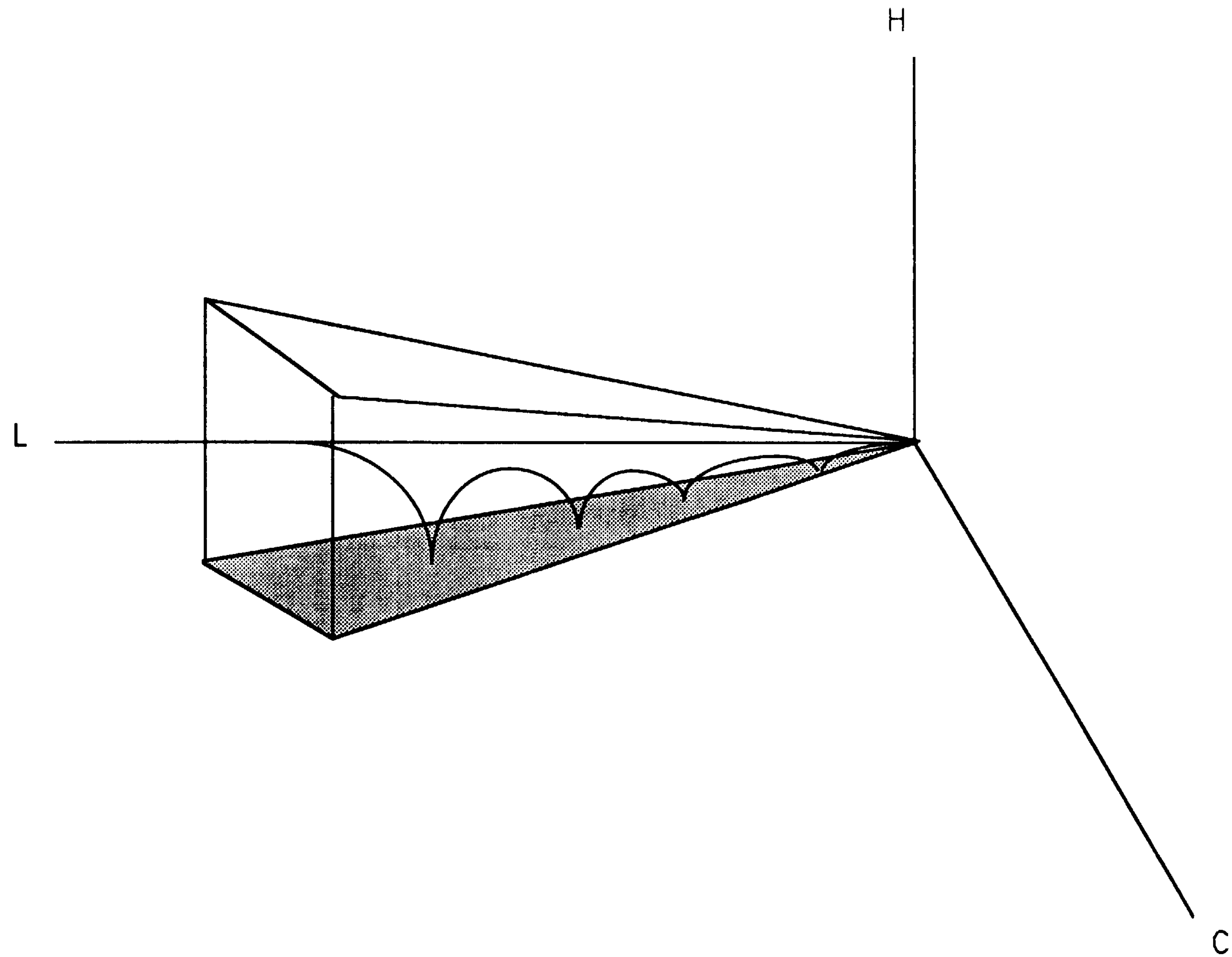
  - STUDYING USE OF NEW TECHNOLOGIES FOR ADAPTIVE CONTROL AND ADAPTIVE FILTERING FOR ROBUST GN&C SYSTEMS

- INTELLIGENT SYSTEMS

  - CONCEPT FOR A CAMERA TRACKING SYSTEM HAS BEEN DEVELOPED

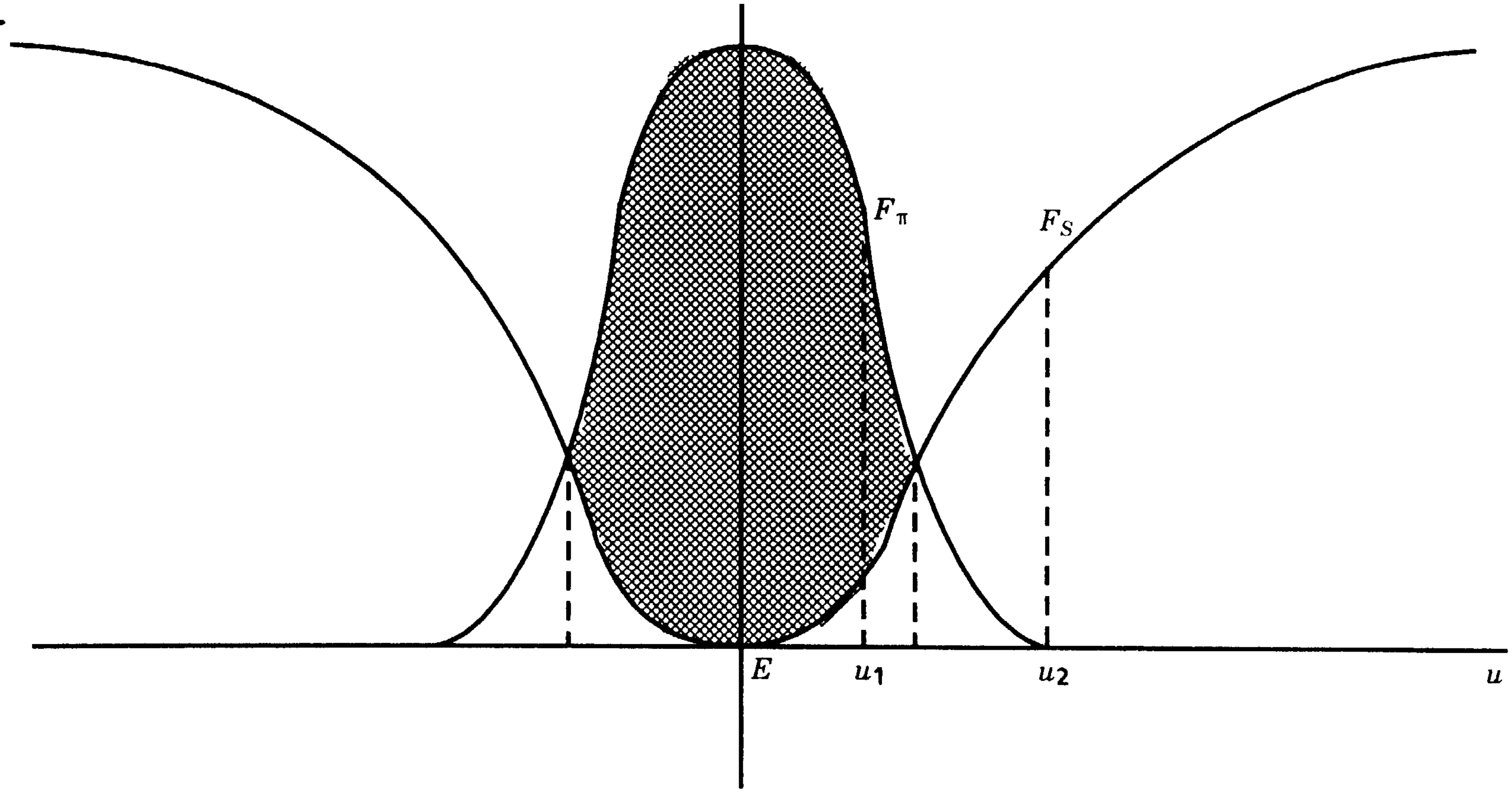
  - STUDYING NEW TECHNOLOGIES FOR OBJECT IDENTIFICATION AND CAUTION/WARNING CAPABILITIES e.g. FUZZY SETS, DEMPSTER-SHAFER THEORY, NEURAL NETWORKS

STRATEGY FOR TRANSLATIONAL CONTROL



Desired corridor size and shape along the approach direction

STRATEGY IN CONTROLLING A PARAMETER U



FOR A GIVEN VALUE OF u, f_π IS COMPARED WITH f_s AND THE LARGER VALUE DICTATES WHETHER ACTION IS TAKEN.

IN THE ABOVE EXAMPLE FOR u_1, $f_\pi > f_s$ AND NO ACTION IS TAKEN.
FOR u_2, $f_s > f_\pi$ AND ACTION IS TAKEN TO DECREASE THE PARAMETER u BY AN AMOUNT WEIGHTED BY THE VALUE f_s.

ELEVATION CONTROL AND AXIMUTH CONTROL

WHEN

$f_s > f_\pi$

THEN

$\Delta V_{R\alpha} = F_{S_\alpha} \omega R k_\alpha - R\dot{\alpha}$

$\Delta V_{R\beta} = F_{S_\beta} \omega R k_\beta - R\dot{\beta}$

FOR CURRENT SIMULATION $k_\alpha = .25$

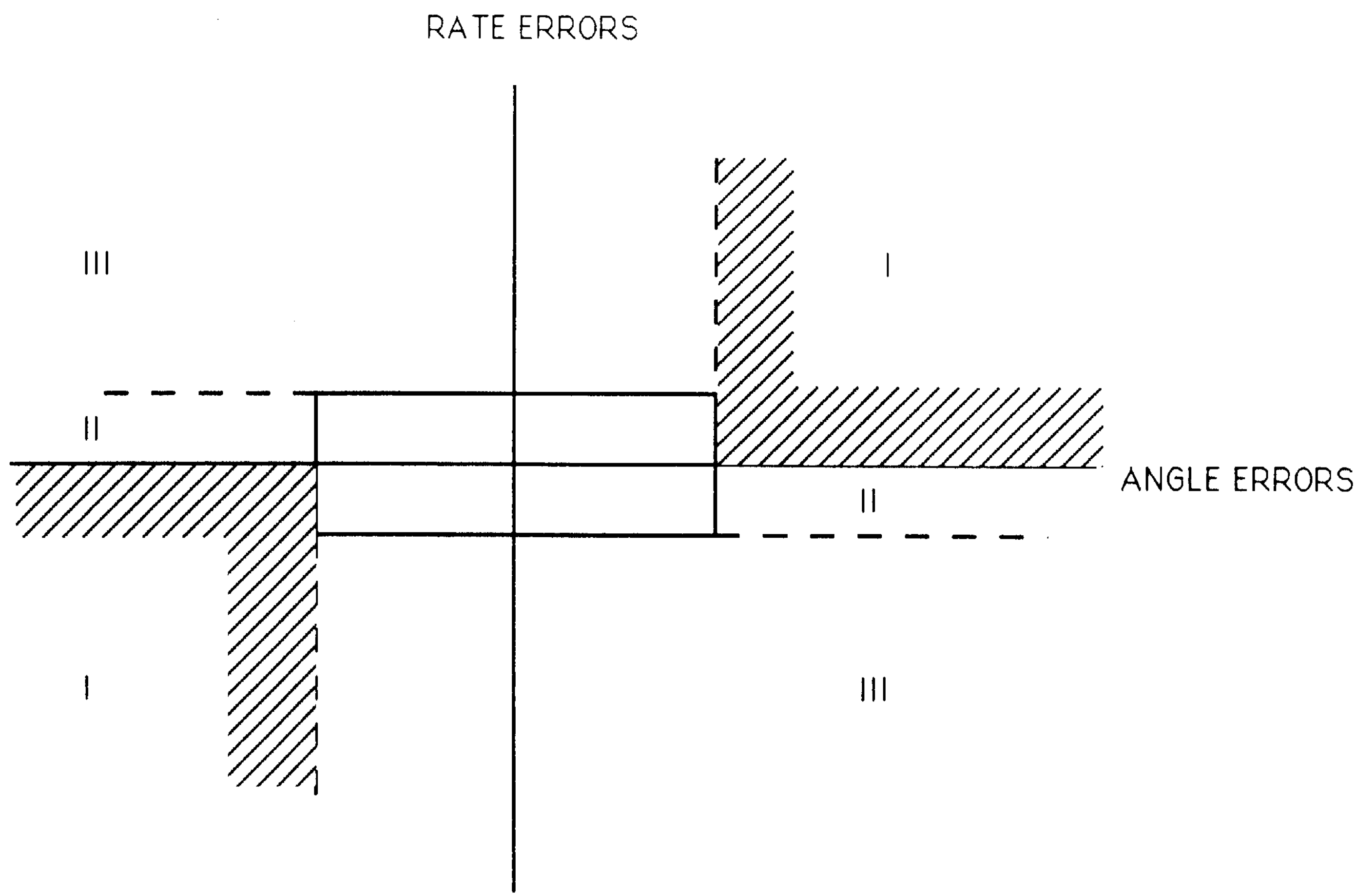
R CONTROL

WHEN

$f_s > f_\pi$

$\Delta R = f_s (R + R/1000)$

TYPICAL SINGLE AXIS PHASE PLANE



REGION I ALWAYS REQUIRES CORRECTION (e.g. THROUGH JETS)

REGION II DOES NOT REQUIRE CORRECTION AS IT WILL SLIDE IN THE PHASE PLANE

REGION III REQUIRES CORRECTION ONLY TO REDUCE OVERSHOOT AND INCREASE CONTROL EFFICIENCY

RULES FOR PHI AND PHI_DOT FOR ROTATIONAL CONTROL

PHI

PHI_DOT	NB	NM	NS	ZO	PS	PM	PB
NB	PM	PM	PS				
NM	PM	PM	PS				
NS	PS	PS	PS				
ZO	PS	PS	ZO	ZO	ZO	NS	NS
PS					NS	NS	NS
PM					NS	NM	NM
PB					NS	NM	NM

KEY :
PB - POSITIVE BIG
PM - POSITIVE MEDIUM
PS - POSITIVE SMALL
ZO - ZERO ZONE
NS - NEGATIVE SMALL
NM - NEGATIVE MEDIUM
NB - NEGATIVE BIG

CURRENT AUTOMATION ACTIVITIES (CONTINUED)

PERFORMANCE OF FUZZY LOGIC BASED CONTROLLERS PRELIMINARY RESULTS

- TRANSLATIONAL CONTROLLER

SCENARIO	MANUAL CONTROL DV REQUIRED	AUTOMATED FUZZY CONTROLLER DV REQUIRED
STATIONKEEPING AT 150' FOR 30 MINUTES	0.54 FT/SEC	0.1 FT/SEC
V-BAR APPROACH FROM 500' TO 40' 25 MINUTE TIME ARRIVAL	2.99 FT/SEC	2.12 FT/SEC

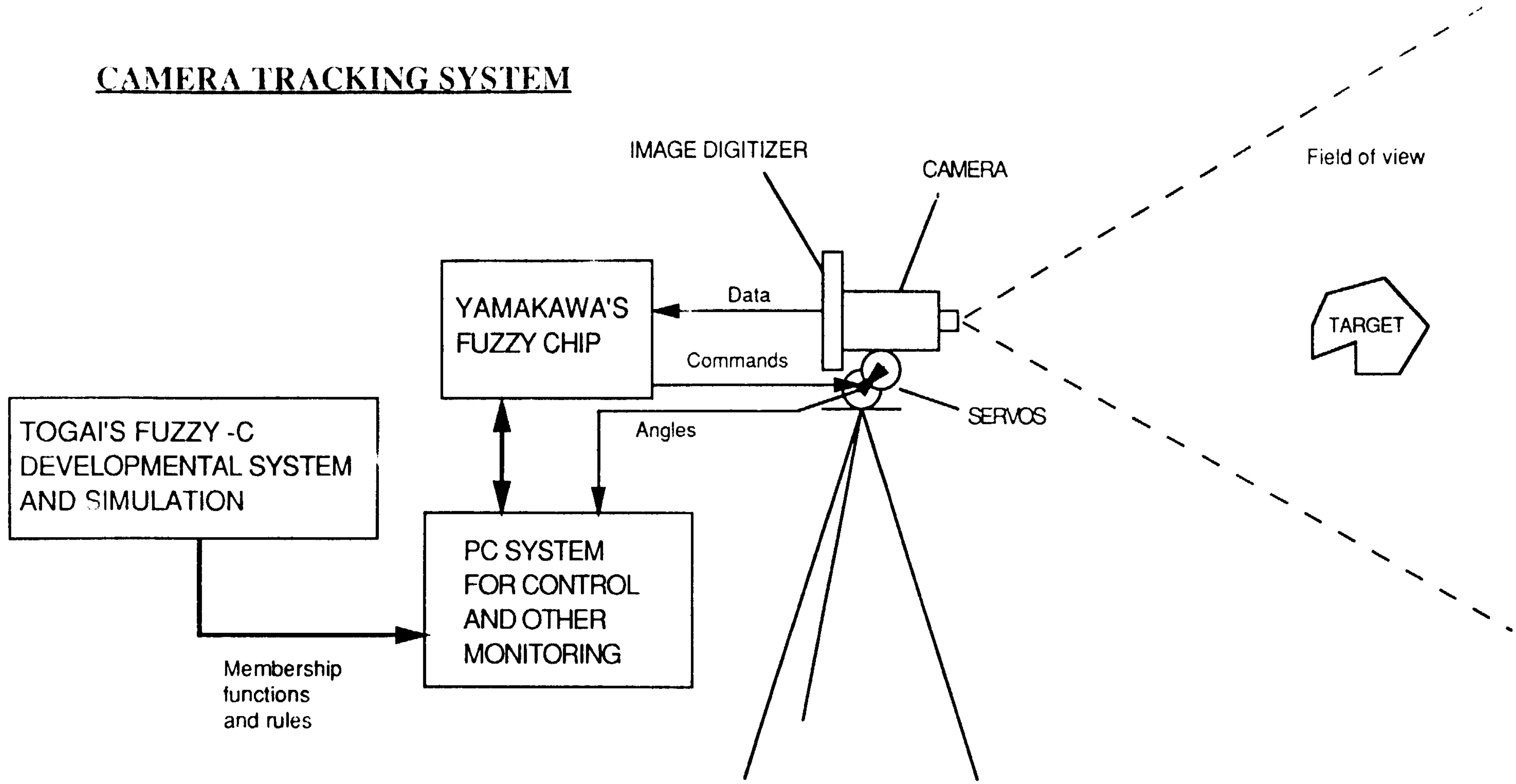
- ATTITUDE CONTROLLER

  - DURING LVLH-HOLD FOR 1000 SEC, FUZZY CONTROLLER USES 50 % OF FUEL CONSUMED BY THE CONVENTIONAL CONTROLLER

  - DURING ATTITUDE MANEUVERS, FUZZY CONTROLLER USES 70 % OF FUEL CONSUMED BY THE CONVENTIONAL CONTROLLER

- ADDITIONAL TESTING IS IN PROGRESS FOR BOTH CONTROLLERS

CAMERA TRACKING SYSTEM

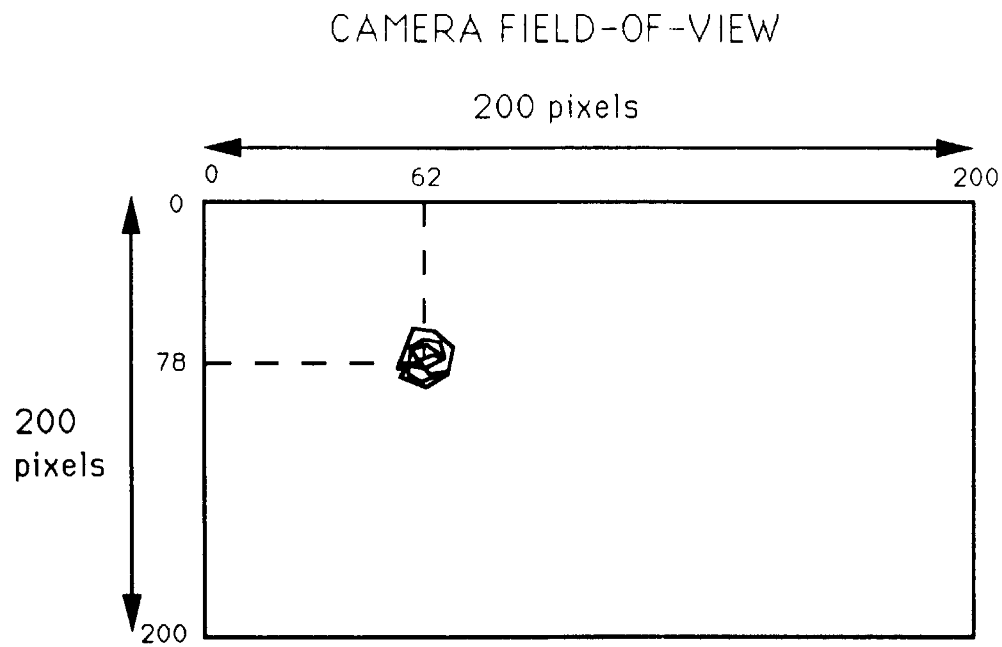


APPLICATIONS :

- TELEROBOTICS OPERATIONS
- ASSEMBLY & MAINTENANCE
- DOCKING MANEUVERS HELP
- TRAFFIC MANAGEMENT INPUTS
- DEBRIS TRACKING, ALERT SYSTEM

ADVANTAGES :

- PASSIVE/ACTIVE TARGETS
- LOW POWER REQUIREMENTS
- DEDICATED CHIPS AVAILABLE TO REDUCE MAIN CPU LOAD



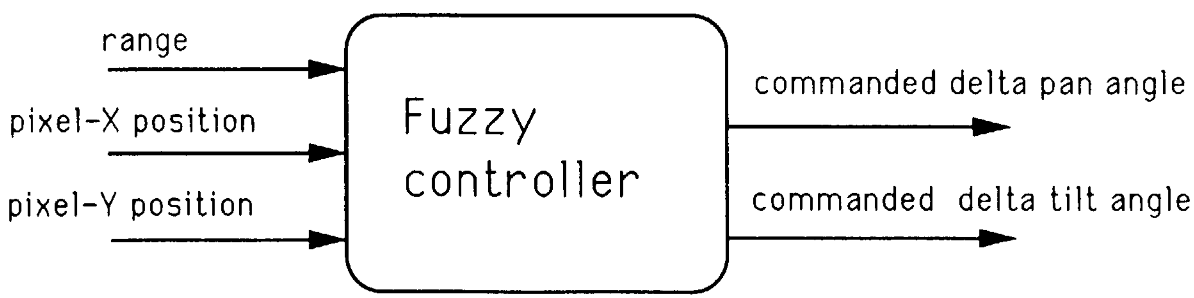
It is assumed that a laser range finder provides the range measurement to fuzzy controller

Camera generates measurements in terms of PIXELS : Where the field of view is divided in 200 by 200 pixel map

Current measurements are 62 and 78.

Fuzzy controller will generate the pan and tilt commands in terms of how much angle to be moved. For example, the output could be 'pan left 2 degrees' and 'tilt up 1 degree'.

The camera FOV system is x along line of sight, y towards right hand and z downward.
In this frame, tilt upward is positive, downward is negative. Pan towards right is positive and towards left is negative.



CONCEPT OF A CAMERA TRACKING SYSTEM

SUMMARY

- THERE ARE SEVERAL RENDEZVOUS AND PROXIMITY OPERATIONS AREAS THAT WILL BENEFIT FROM AUTOMATION AND AUTONOMOUS CONCEPTS

    - TRAJECTORY CONTROL
    - INTELLIGENT SENSORS

- OPERATIONAL EFFICIENCY CAN BE ACHIEVED THROUGH AUTONOMOUS OPERATIONS FOR FUTURE SPACE MISSIONS

- THERE IS A NEED TO INITIATE THE ACTIVITY

    - TO DEFINE DESIGN REFERENCE MISSIONS AND DEVELOP DETAIL MISSION SCENARIOS

    - TO DEMONSTRATE ROBUST FAULT DETECTION, ISOLATION AND RESOLUTION (FDIR) CAPABILITIES THAT CAN MIGRATE TO ONBOARD ENVIRONMENT

AR&D Strategies for a Mars Sample Return Mission

Autonomous Rendezvous and Docking Conference

Johnson Space Center, Houston, Texas

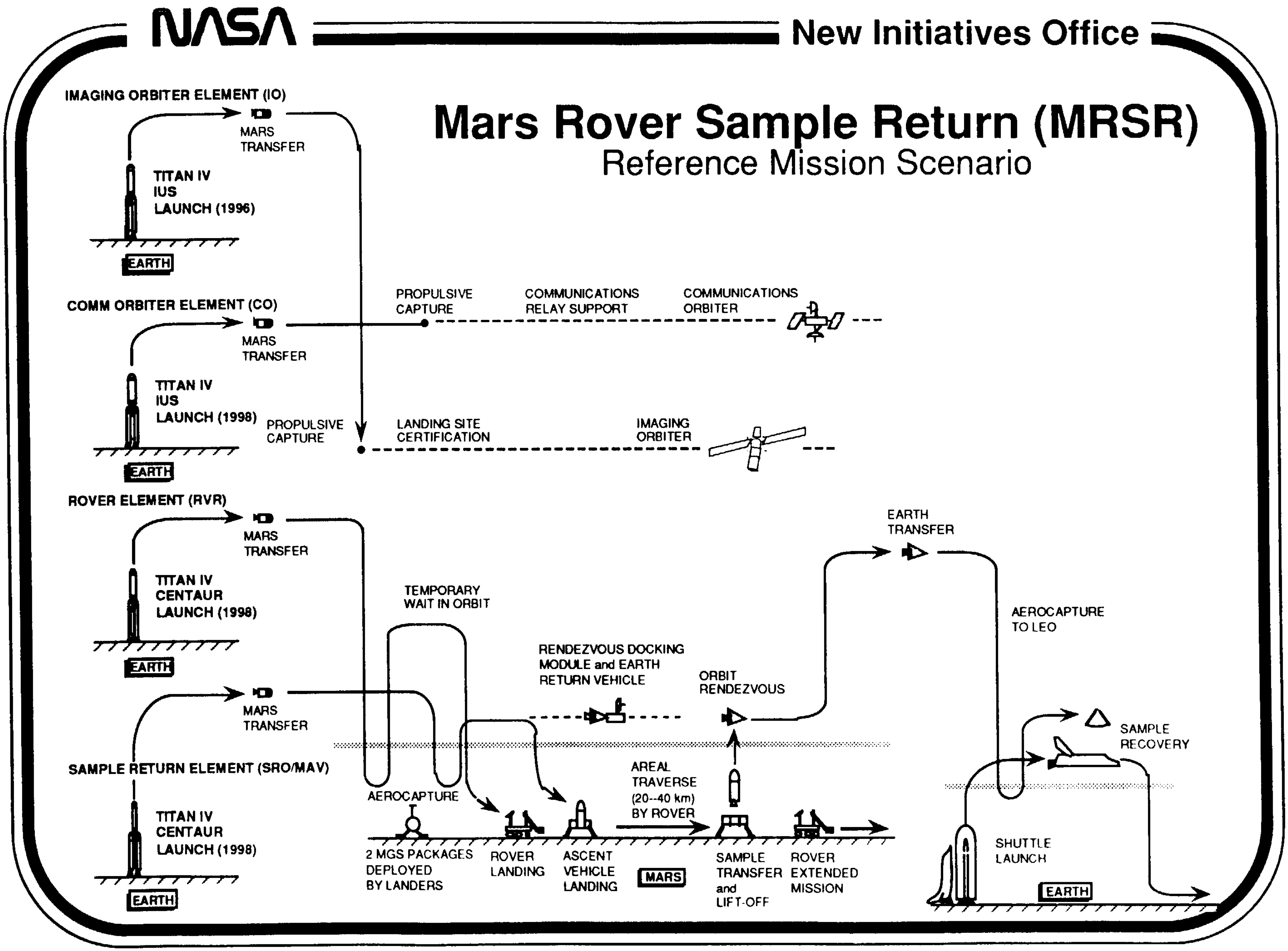
Stephen Bailey, System Engineer
Lunar/Mars Exploration Projects, Human Robotic Spacecraft Office

Aug 16, 1990

MRSR Status Update

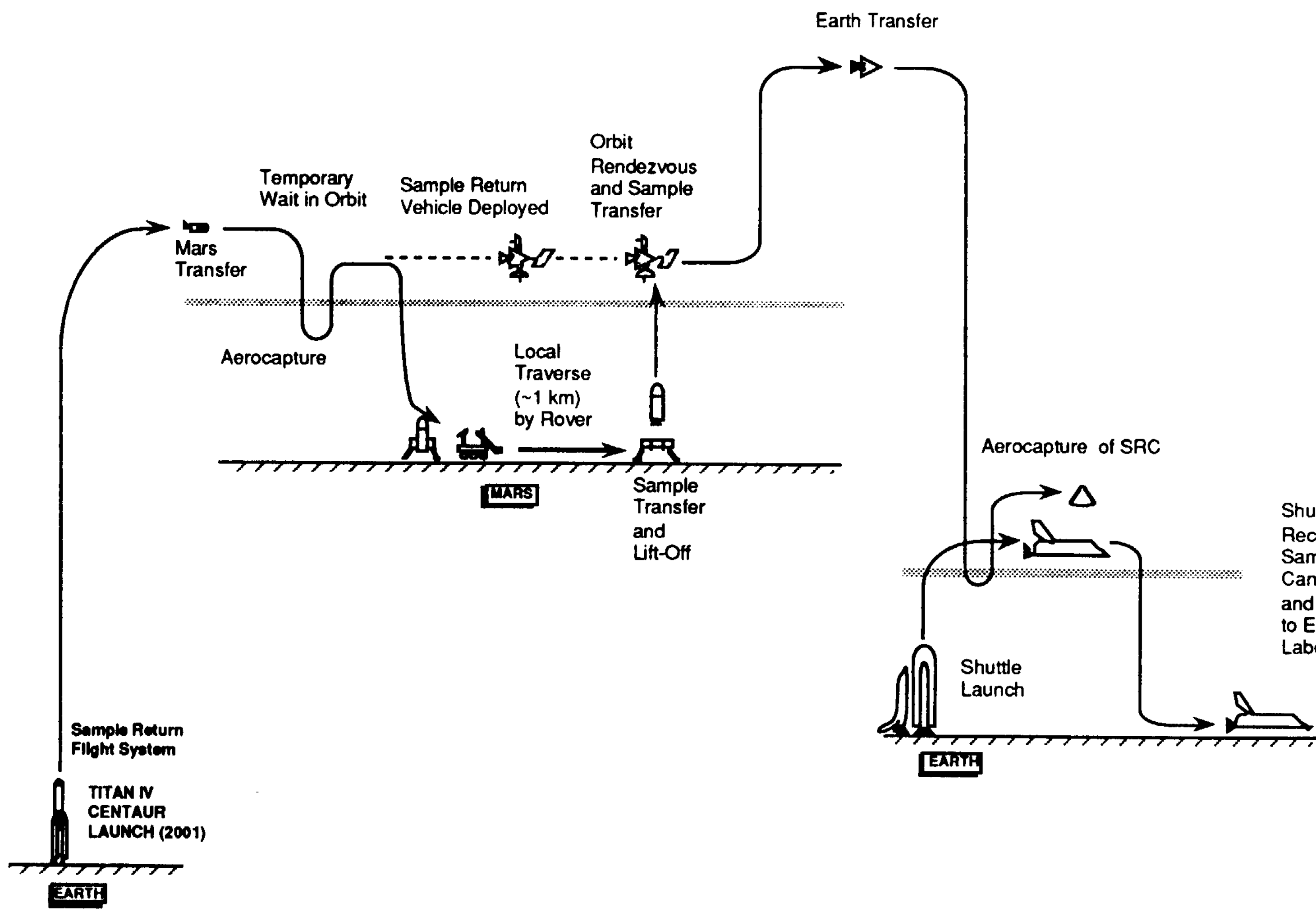
Mars Rover Sample Return

- Studied by the Jet Propulsion Lab and JSC jointly for three years, Phase A study completed this year
- Originally targeted for a 1998 launch
- Space Exploration Initiative has provided a new context for the mission, and a new and as yet incompletely defined set of requirements
- Mars Sample Return continues to be emphasized as a science mission, and as a necessary precursor mission to human flight
  - biohazard evaluation, planetary protection
  - crew safety - esp. toxicity
  - surface characterization for engineering design
  - in-situ resource utilization

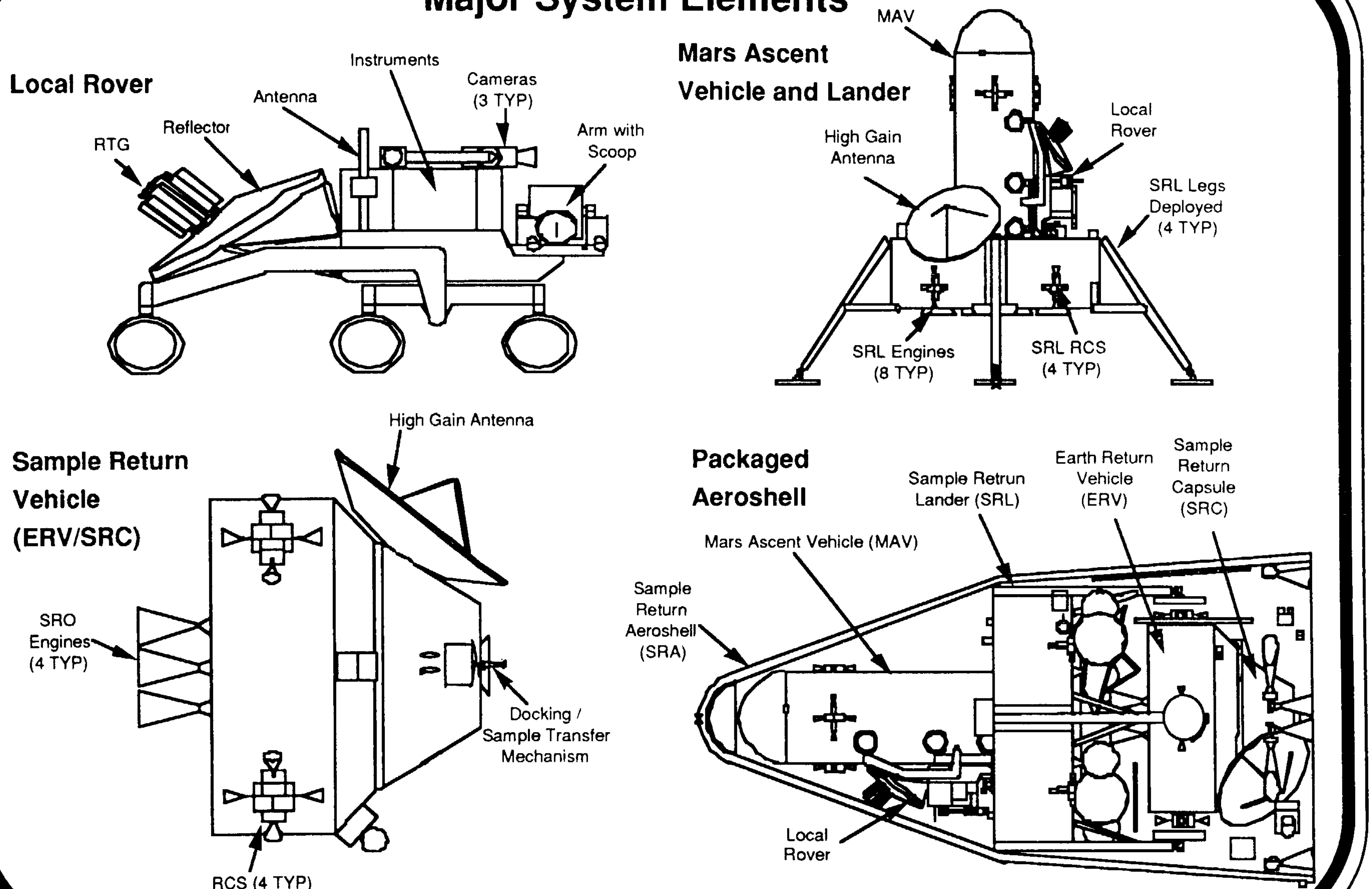

NASA
New Initiatives Office
Mars Rover Sample Return (MRSR)
Reference Mission Scenario
IMAGING ORBITER ELEMENT (IO)
MARS TRANSFER
TITAN IV
IUS
LAUNCH (1996)
EARTH
COMM ORBITER ELEMENT (CO)
MARS TRANSFER
TITAN IV
IUS
LAUNCH (1998)
EARTH
PROPULSIVE CAPTURE
COMMUNICATIONS RELAY SUPPORT
COMMUNICATIONS ORBITER
PROPULSIVE CAPTURE
LANDING SITE CERTIFICATION
IMAGING ORBITER
ROVER ELEMENT (RVR)
MARS TRANSFER
TITAN IV
CENTAUR
LAUNCH (1998)
EARTH
TEMPORARY WAIT IN ORBIT
RENDEZVOUS DOCKING MODULE and EARTH RETURN VEHICLE
ORBIT RENDEZVOUS
EARTH TRANSFER
AEROCAPTURE TO LEO
MARS TRANSFER
SAMPLE RETURN ELEMENT (SRO/MAV)
TITAN IV
CENTAUR
LAUNCH (1998)
EARTH
AEROCAPTURE
AREAL TRAVERSE (20--40 km) BY ROVER
2 MGS PACKAGES DEPLOYED BY LANDERS
ROVER LANDING
ASCENT VEHICLE LANDING
MARS
SAMPLE TRANSFER and LIFT-OFF
ROVER EXTENDED MISSION
SAMPLE RECOVERY
SHUTTLE LAUNCH
EARTH

Sample Return with Local Rover

Mission Scenario

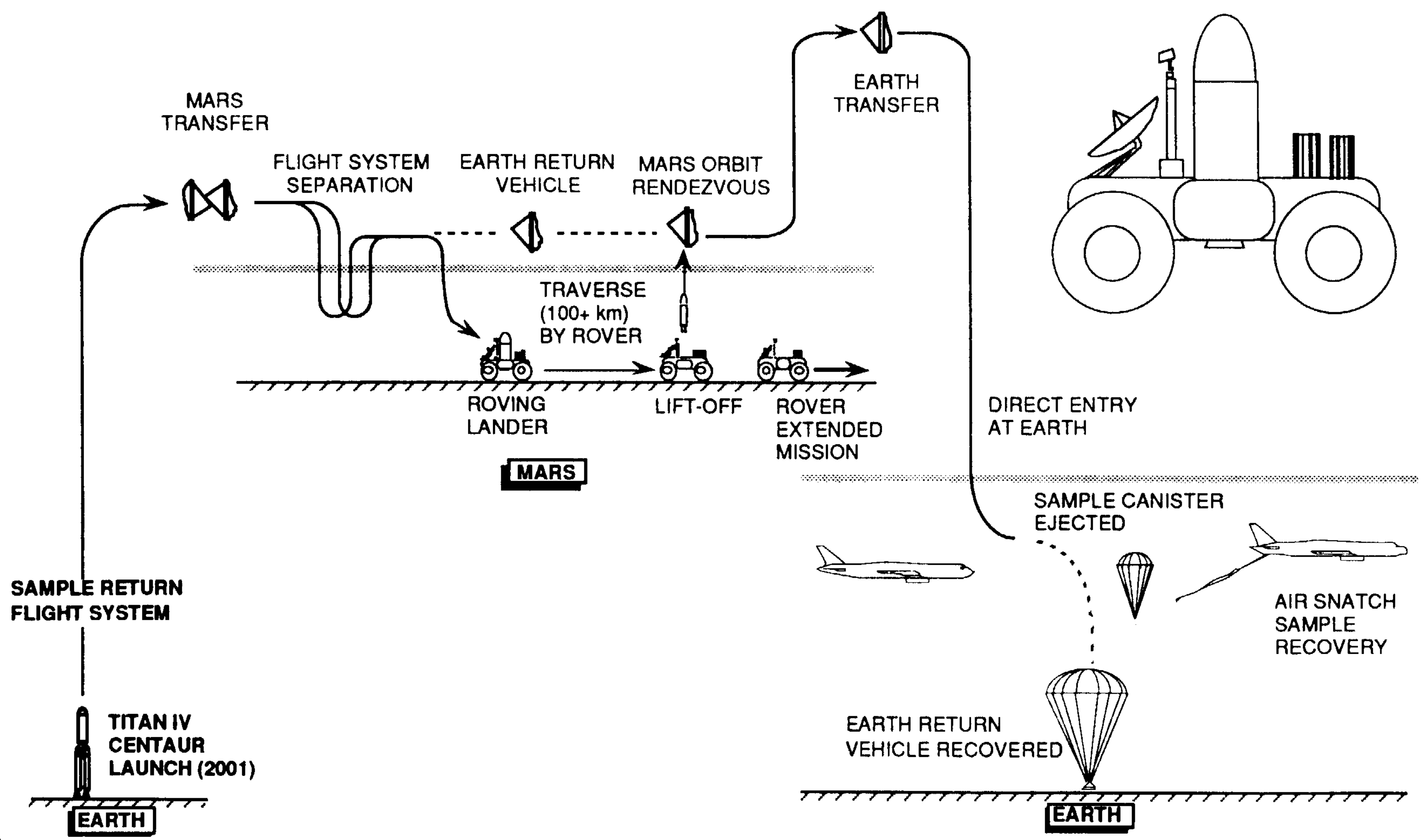


Major System Elements



NASA New Initiatives Office

Alternate 90 Day Study Human Exploration Emphasis
Mission Scenario



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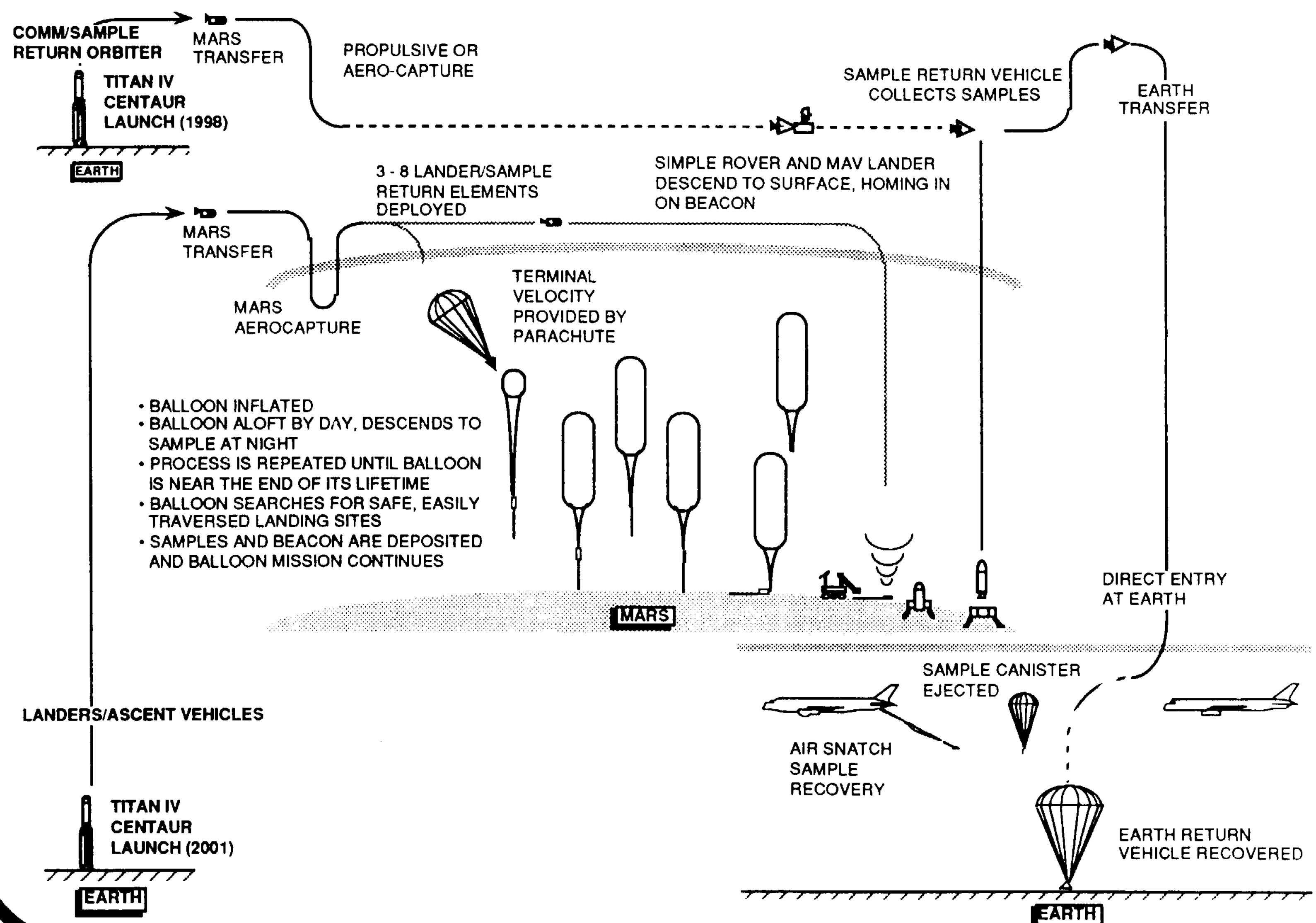
"Wandering Balloon" Mission Scenario



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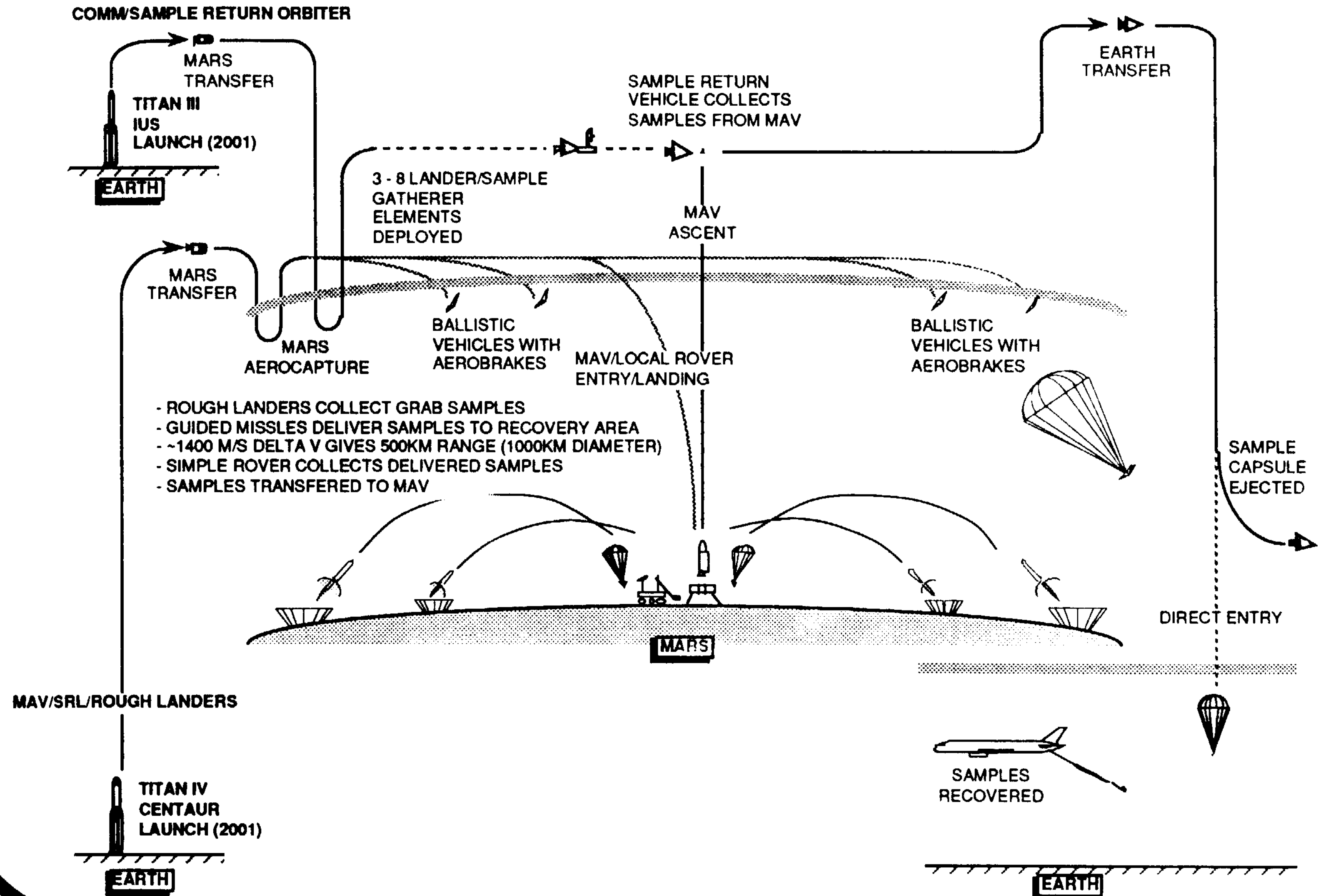
"Basketball Hoop" Mission Scenario

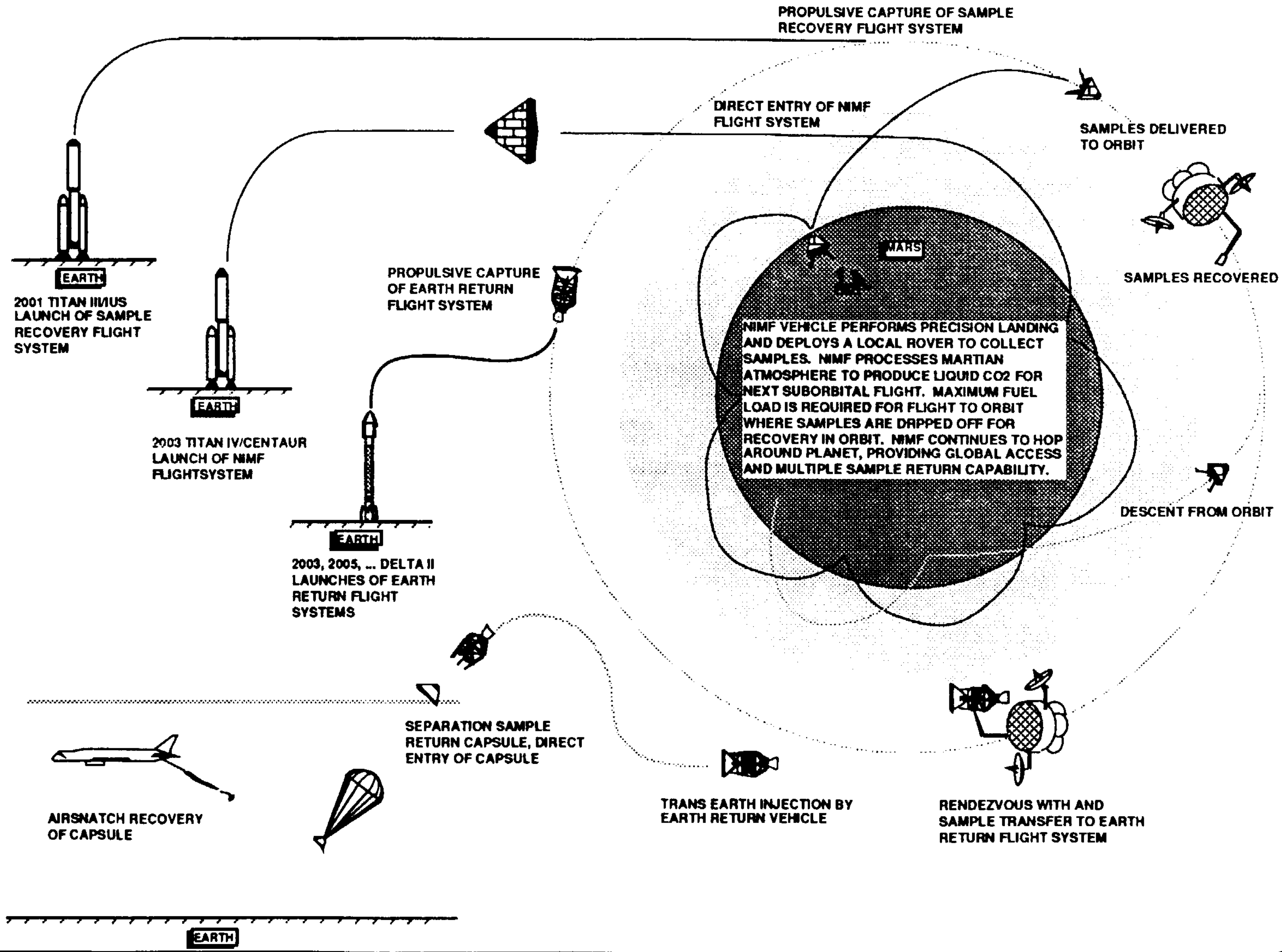


- ROUGH LANDERS COLLECT GRAB SAMPLES
- GUIDED MISSLES DELIVER SAMPLES TO RECOVERY AREA
- ~1400 M/S DELTA V GIVES 500KM RANGE (1000KM DIAMETER)
- SIMPLE ROVER COLLECTS DELIVERED SAMPLES
- SAMPLES TRANSFERED TO MAV

New Initiatives Office

High Technology Leverage Mission Scenario

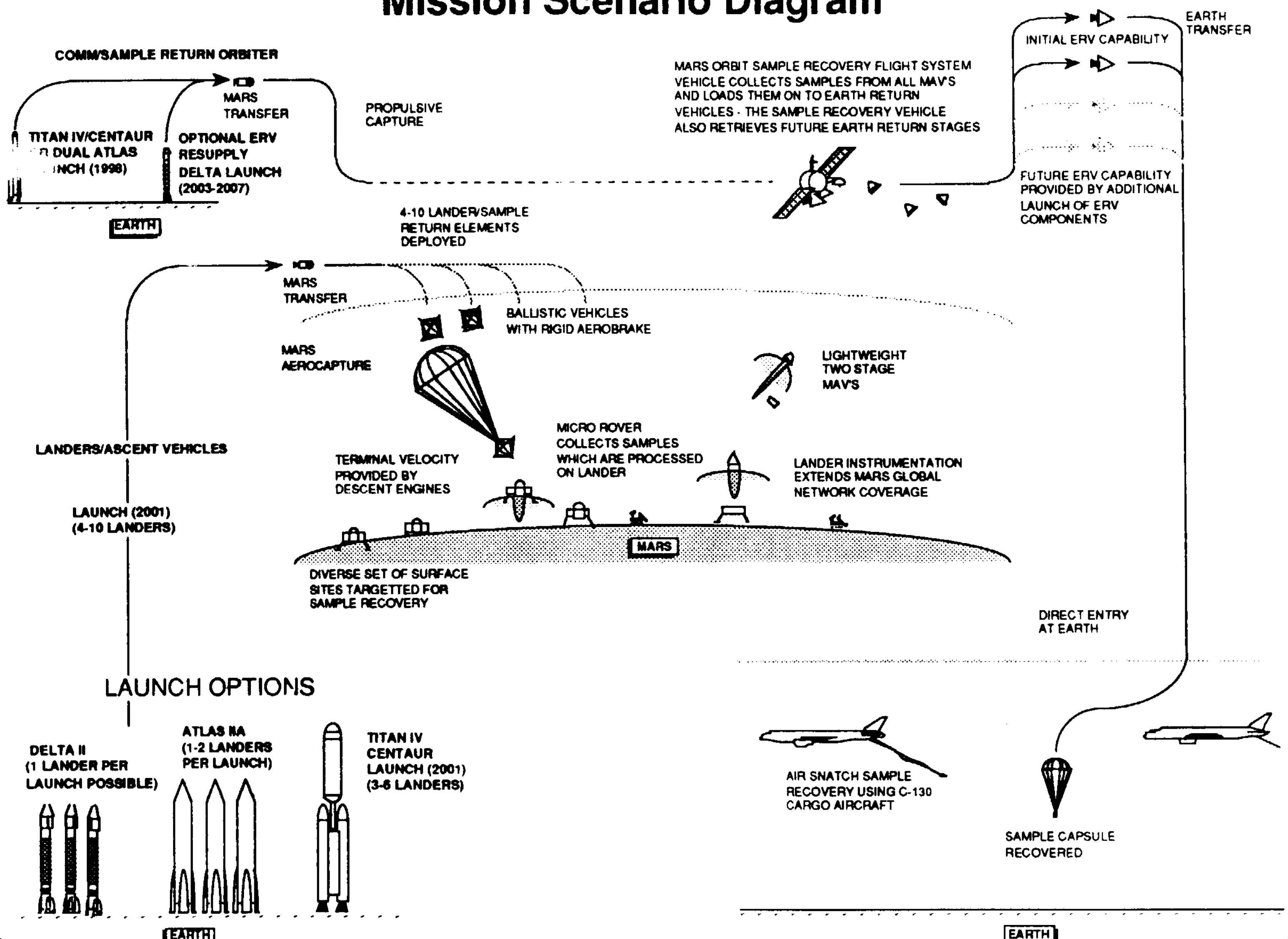
Mission Scenario Diagram



NASA — New Initiatives Office

Evolutionary Mars Sample Return Mission Scenario

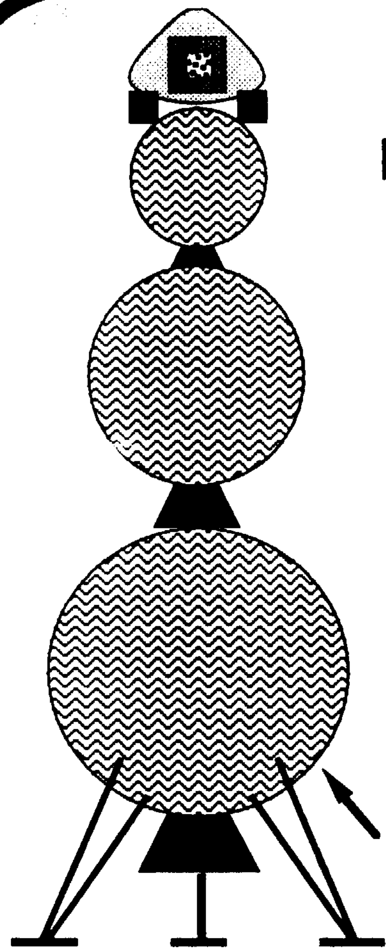
Mission Scenario Diagram



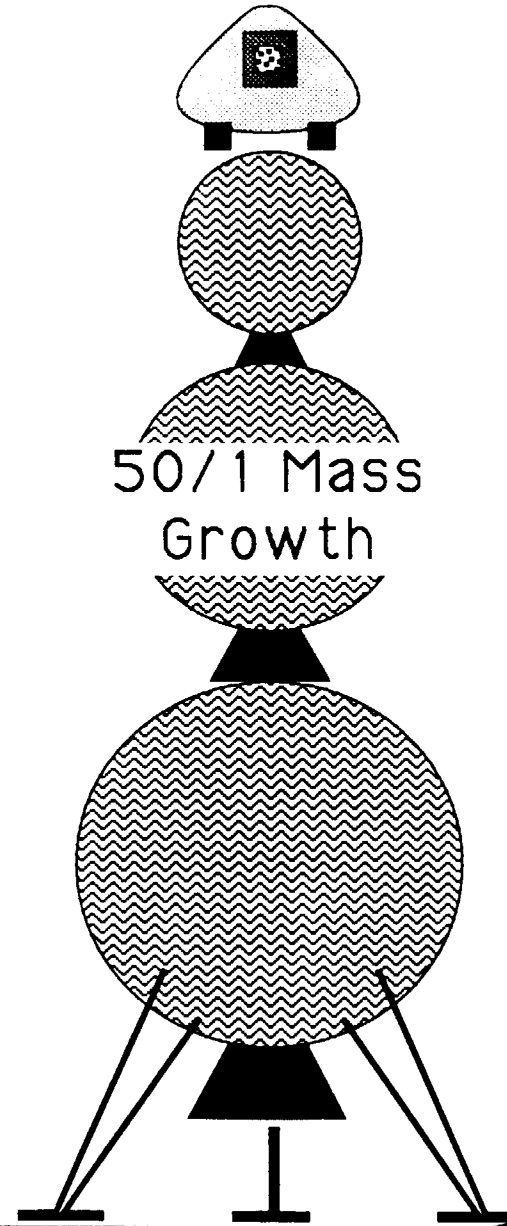
Mars Sample Return and AR&D

- Autonomous Rendezvous and Docking are Common Features of all of These Scenarios - Why?

Direct Return Approach



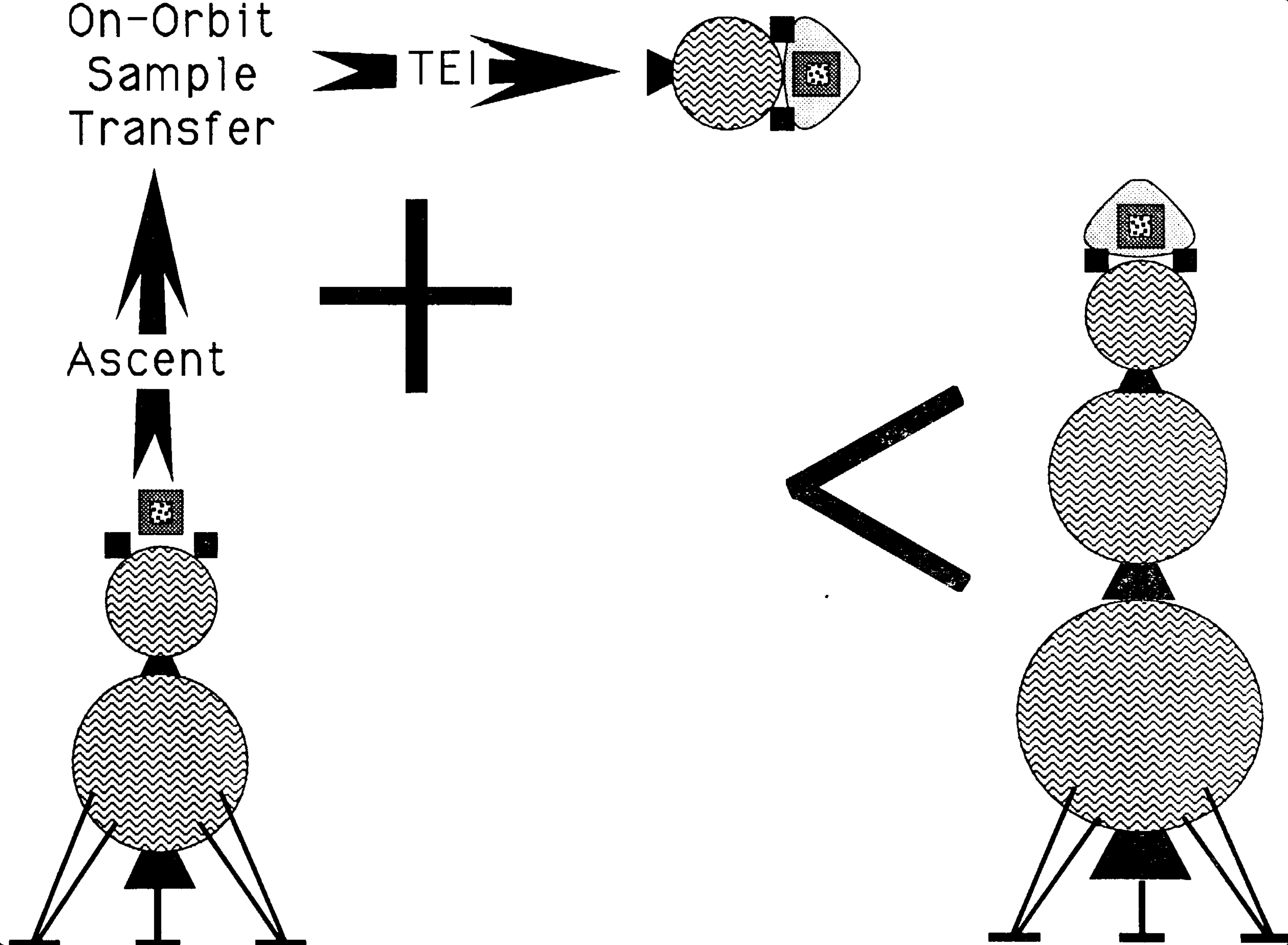
Requirements:
- Communication
- Navigation
- Attitude Control
- Midcourse
- Reliability, Fault Tolerance
- Power



Samples
Sample Container
Sample Capsule
Avionics:
- Ascent
- On-orbit
- Earth Return

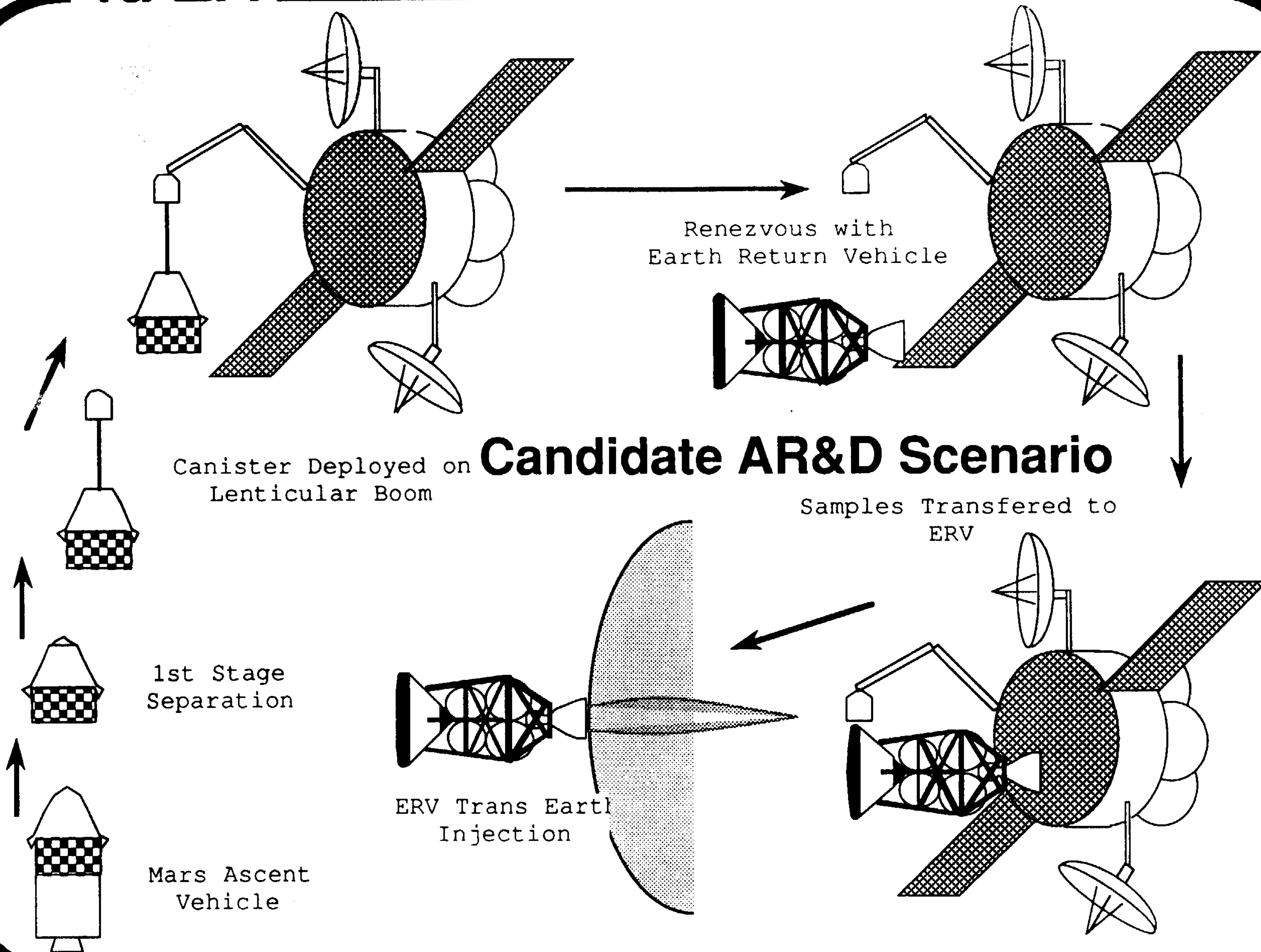
NASA New Initiatives Office

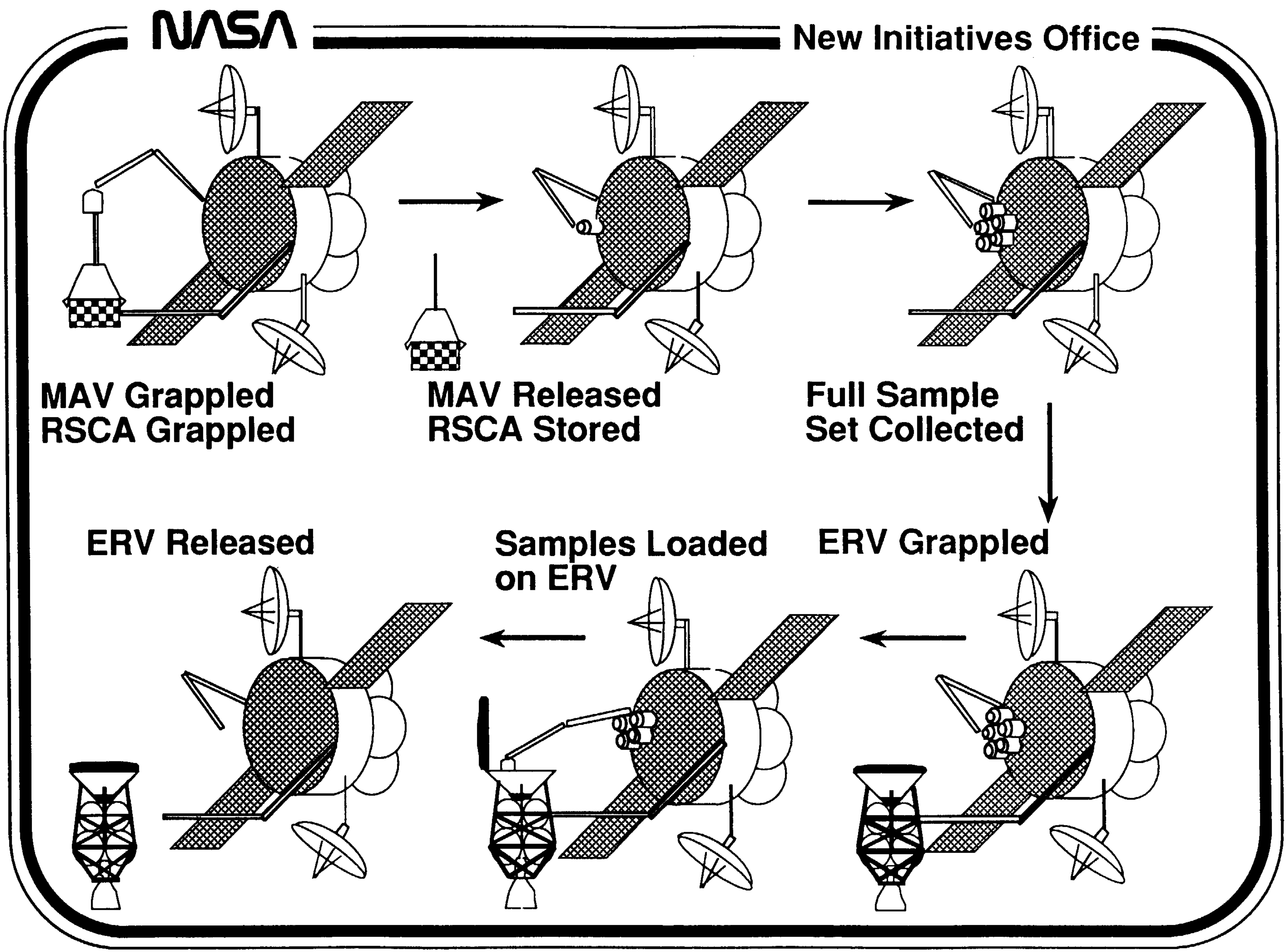
On-Orbit Sample Transfer



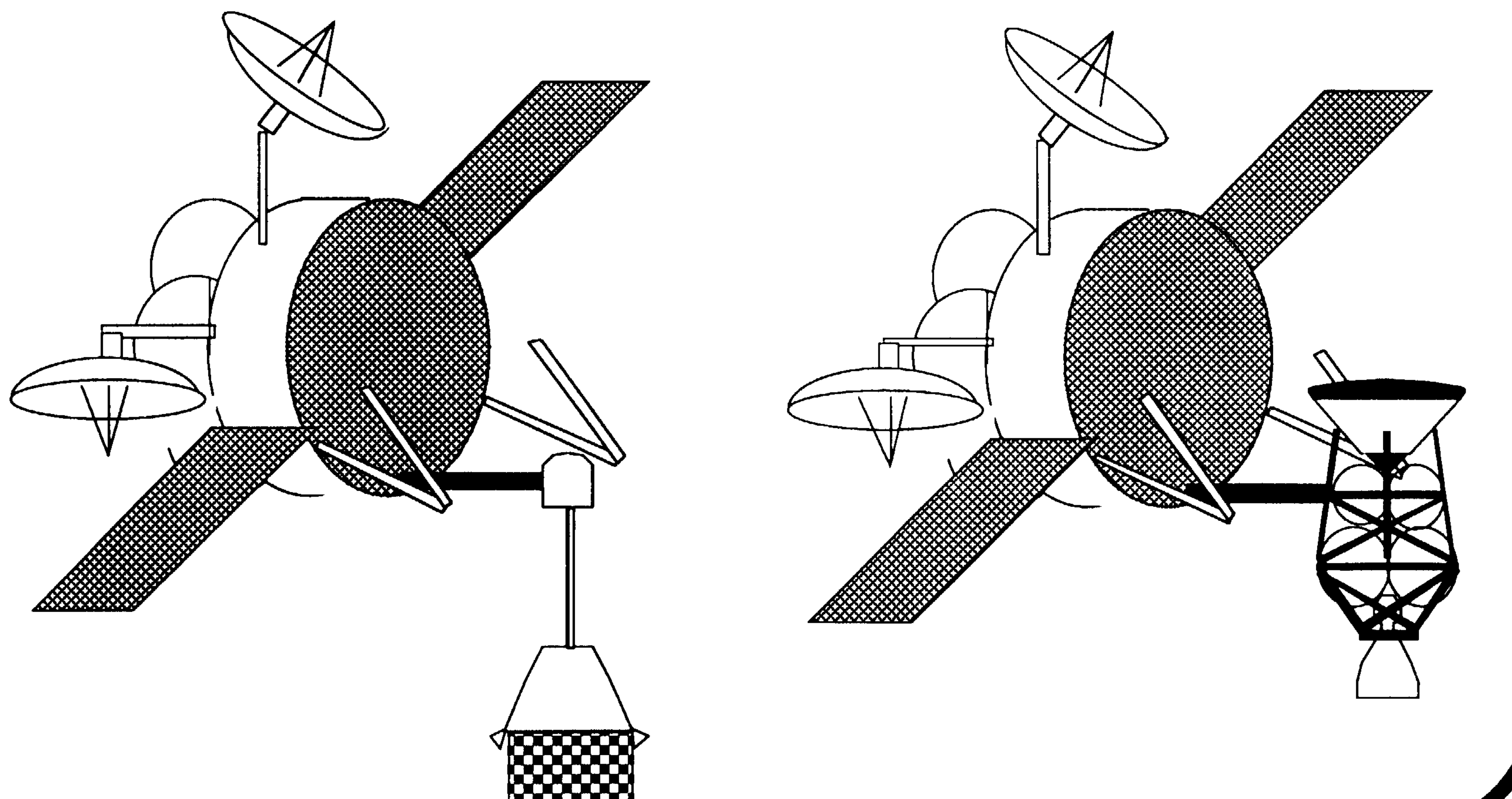
New Initiatives Office

Candidate AR&D Scenario




NASA
New Initiatives Office
MAV Grappled
RSCA Grappled
MAV Released
RSCA Stored
Full Sample
Set Collected
ERV Grappled
Samples Loaded
on ERV
ERV Released

Fixed Docking "Stinger"



AR&D Requirements for a Small/Simple Ascent Vehicle

Mars Ascent Vehicle (MAV)

- MAV must execute ascent trajectory with modest known dispersions
- MAV must be passively stabilized in a manner compatible with thermal control of the sample
- MAV can employ only very light navigation aids (low power beacon, reflective paint, tape, or cubes, ...)

Rendezvous Orbiter (RO)

- RO must acquire a low signal strength signal from which it can estimate angles and range to target
- RO must close to within acquisition range of precision (near field/docking sensor) sensor
- RO must perform all maneuvers in such a way as to not disturb the attitude stability of the MAV
- The RO must achieve a positive connection to the Return Sample Canister Assembly (RSCA) and initiate release from the MAV

What's Next ?

Activities for FY '91

- Work with JPL to Provide Inputs for Evolving SEI Architectures
- Follow Closely Code S desires for Mars Sample Return
- Continue to Study Issues Generic to Mars Sample Return
  - Planetary Protection (back contamination)
  - Mobility, Trafficability & Surface Operations
  - Capture Method at Mars (aerocapture, direct entry, ...)

  :

  :

  - Autonomous Rendezvous and Docking
    - System Trade Studies
    - Sensor Hardware
    - Operation Concepts
    - Docking, Grappling, Attach/Release Mechanisms

TRW Federal Systems Division
Space & Technology Group

AUTONOMOUS PROXIMITY

AND

DOCKING TECHNOLOGIES

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FOR PRESENTATION AT

NASA/JSC AUTONOMOUS RENDEZVOUS
AND DOCKING CONFERENCE

AUGUST 15-16, 1990

HOUSTON, TEXAS

1 INTRODUCTION

Autonomous spacecraft rendezvous and docking algorithms are being developed at TRW and tested at the MSFC Flight Robotics Laboratory. The algorithms are tested using a working docking sensor developed by MSFC and a robotic manipulator system with full scale mock-ups of spacecraft. The simulations being run operate in real-time using full scale motion and 6 degree of freedom (DOF) control. The purpose of the algorithm development and testing is to understand the issues related to autonomous proximity and docking operations and to develop and demonstrate the capability of performing autodocking. An additional goal is the development of docking sensor requirements and the evaluation and testing of sensor technologies.

This paper describes work being performed and progress which has been made in the area of autodocking. Observations and conclusions drawn from actual docking tests are presented. Results from the test floor are very promising and rapid progress in control algorithm and sensor development is underway.

2 SENSOR REQUIREMENTS AND OPERATIONAL CONSTRAINTS

The sensor is the key component of the autonomous proximity operations and docking system. The sensor must generate data of sufficient fidelity to support the functions of proximity operations leading to a successful dock. The sensor must generate accurate translational and rotational data that specify the target vehicle position and orientation with respect to the homing spacecraft. These data feed the control software which guides the homing spacecraft to dock. All flight rules that apply to piloted docking must be followed by the autonomous system, bounding the data requirements and accuracy the sensor must achieve.

The operational constraints on autonomous proximity operations include the flight rules of a mission, viewing conditions and the ability to adapt to flight discontinuities, such as loss of target lock. Operational constraints such as safe approach velocities, standoff range for target acquisition, docking abort procedures, safe approach paths, and docking error tolerance need to be defined for each mission. The sensor and the control loop must work in harmony in order for the system to operate within the defined mission constraints.

The sensor must maintain sensor lock during all nominal flight conditions of sun angle, darkness, closure rates and rotational rates. These conditions are specified for particular mission profiles. Flight rules and procedures determine where and when in the autodocking procedure that the sensor must have the target within its usable field of view and at what range the sensor needs to acquire lock and begin generating data for the control loop.

The sensor needs the ability to identify loss of target lock and to re-establish it. Discontinuities, such as spurious sun reflections and temporary loss of target illumination, may cause the sensor to be confused. It must be able to detect these events and recover in a timely manner so as not to impede a successful docking effort.

These autodocking sensor performance requirements are a function of the control algorithms and will increase or decrease as the control system capabilities change and more test data is collected.

AUTONOMOUS DOCKING SYSTEM REQUIREMENTS

- ACQUISITION AND TRACKING RANGE
  - 50 FEET TO DOCKING CONTACT
- TARGET ORIENTATION
  - FLY AROUNDS PERFORMED AS NEEDED TO ACHIEVE SENSOR LOCK
- SENSOR UPDATE CYCLE
  - MUST BE WITHIN THE CYCLE TIME OF CONTROL LOOP
- TARGET COOPERATION
  - TARGET MUST HAVE PASSIVE AIDS FOR ACQUISITION AND TRACKING
- DOCKING SENSOR PERFORMANCE REQUIREMENTS

OUTPUT PARAMETER	RANGE LIMITS	ALLOWABLE ERROR
RANGE	0.0 - 50 ft	0.01 ft at dock
RANGE RATE	±0.2 ft/sec	0.01 ft/sec at dock
BEARING ANGLE	±10 deg	0.42 deg
BEARING ANGLE RATE	0.6 deg/sec	0.06 deg/sec
ATTITUDE (PITCH & YAW)	±45 deg	0.2 deg
ATTITUDE (ROLL)	±180 deg	0.42 deg
ATTITUDE RATE	±6 deg/sec	0.1 deg/sec

3 CONTROL ALGORITHM DEVELOPMENT AND EVOLUTION

Various control algorithm concepts are being studied. These include phase plane, piecewise linear C-W approach, pure C-W approach and hybrid phase plane and C-W approach control loops. The phase plane control algorithm has been tested through simulations and works very well and is easy to adjust to obtain the desired performance. The piecewise linear C-W approach algorithm has been tested more extensively using real sensor hardware and has proven to be quite tricky to tune for adequate performance and is not intuitive in its behavior. Future versions of the control algorithm will be a hybrid of phase plane and C-W approach techniques.

The first translational control loop implemented was a phase plane controller. Software simulations of this control loop show very good performance. Separate control loops are used for each translational axis. The Z loop is identical to the Y loop. The inputs to the control loops are a position error signal and a velocity error signal. The X axis phase plane is like the Y and Z loops except that the error signals are generated in a different way.

The piecewise linear Clohessy-Wiltshire approach control loop uses C-W equations to predict the velocity needed to get from the current location to a desired location in a given amount of time. The desired points are computed along a line with equal spacing between points. This causes the goal point to move with a constant linear velocity along a line. Hence the name piecewise linear C-W approach.

This is the control loop which we tested extensively at the MSFC Flight Robotics Laboratory. This technique works but it is flawed. A major flaw is the lack of adequate velocity control. If the current position strays from the desired position too far, the velocity to get the trajectory back on track will be high. This causes the system to overshoot. Another problem with the piecewise linear C-W approach is that it is difficult to control the system since position and velocity deadbands and limits cannot be directly specified.

A third approach to the control loop design is to use a pure C-W approach. This method uses a minimum energy approach and is thus the most fuel efficient. It differs from the piecewise linear C-W approach in that the trajectory is allowed to follow a natural path determined by orbit dynamics, rather than being constrained to a straight line. A disadvantage to this type of approach is the computational cost of each control cycle.

A pure C-W control loop is best suited for a long range approach to get the chase vehicle into close proximity to the target spacecraft. On such an approach, the updates do not have to be performed very frequently so the computational penalties are diminished.

We have found that the phase plane control loops produce very good docking performance and are easily tuned for the desired behavior. This type of control loop is more intuitive in its behavior than the C-W equation based control schemes and it is much easier to accurately control the position and velocity of the vehicle.

Perhaps the best approach to solving the problem of autonomous proximity operations and autonomous docking would be to use a hybrid approach. For proximity operations it is appropriate to use a slower more fuel efficient control scheme. For docking operations, it is important to maintain a high degree of control and fuel usage becomes a secondary concern. A combination of a pure C-W approach during the terminal target rendezvous and maneuvering phase and a phase plane control loop for the docking and close proximity operations would be appropriate.

CONTROL ALGORITHM DEVELOPMENT

- PHASE PLANE CONTROL LOOP
  - GOOD PERFORMANCE
  - INTUITIVE CONTROL PARAMETERS
  - EASY TO TUNE FOR DESIRED PERFORMANCE
  - COMPUTATIONALLY EFFICIENT
- PIECEWISE LINEAR CLOHESSY-WILTSHIRE (C-W) APPROACH CONTROL LOOP
  - SIMILAR TO EXISTING STATIONKEEPING ALGORITHMS
  - DIFFICULT TO ADJUST PARAMETERS FOR DESIRED RESPONSE
  - COMPUTATIONALLY EFFICIENT
- PURE C-W APPROACH CONTROL LOOP
  - NEEDS BRAKING LOGIC TO PREVENT POSITION OVERSHOOT
  - COMPUTATIONALLY EXPENSIVE
  - SUITABLE FOR LONG RANGE APPROACH
  - VERY FUEL EFFICIENT
- HYBRID PHASE PLANE AND C-W APPROACH CONTROL LOOP
  - BEST OF BOTH WORLDS
  - TIGHT CONTROL WHEN NEEDED FOR DOCKING
  - FUEL EFFICIENCY AND SLOW CYCLE TIMES FOR APPROACH

4 SIMULATION VALIDATION

Autonomous docking is being simulated at the NASA MSFC Flight Robotics Laboratory using an optical sensor, a full motion robotic manipulator arm, mock-ups, and a 6 DOF dynamics simulator. The robotic manipulator arm is used to move a full size mock-up of a chase vehicle in a large room with a mock-up of the docking surface of a target spacecraft mounted on a wall. Numerous simulation runs were performed and data was collected for sensor and control loop performance analysis.

In order to get meaningful results from a simulation it is necessary to validate it so that the results can be trusted. The dynamics portion of the simulation was validated during the OMV program by running and documenting an extensive set of test cases. The interfaces with the robotic arm were validated by performing calibration procedures.

The simulation system is composed of several computers which are in communication with each other. Two computers are used for controlling the robotic manipulator arm, one computer is used for processing the sensor data and doing image processing, and one computer is used to run the real time 6 DOF dynamics simulation. The dynamics simulation computes the state vectors for the target and chase spacecraft and updates these states in sync with real time. The dynamics models include the control loops, thrusters, mass properties, and environmental forces. The state information from the dynamics simulation is sent to the arm controller which positions the arm and reports status. The sensor control computer computes relative positions and attitudes and sends data to the arm controller which in turn forwards the sensor data to the dynamics simulator. The dynamics simulator uses the sensor data to drive the control loops and determine the next state. An audible feedback feature was added to the system so that thruster activity could be discerned. The audio system reports X, Y, Z, pitch, yaw and roll thruster firings and is a very useful aid to understanding the behavior of the control loop as the motion of the mock-up is being visually monitored.

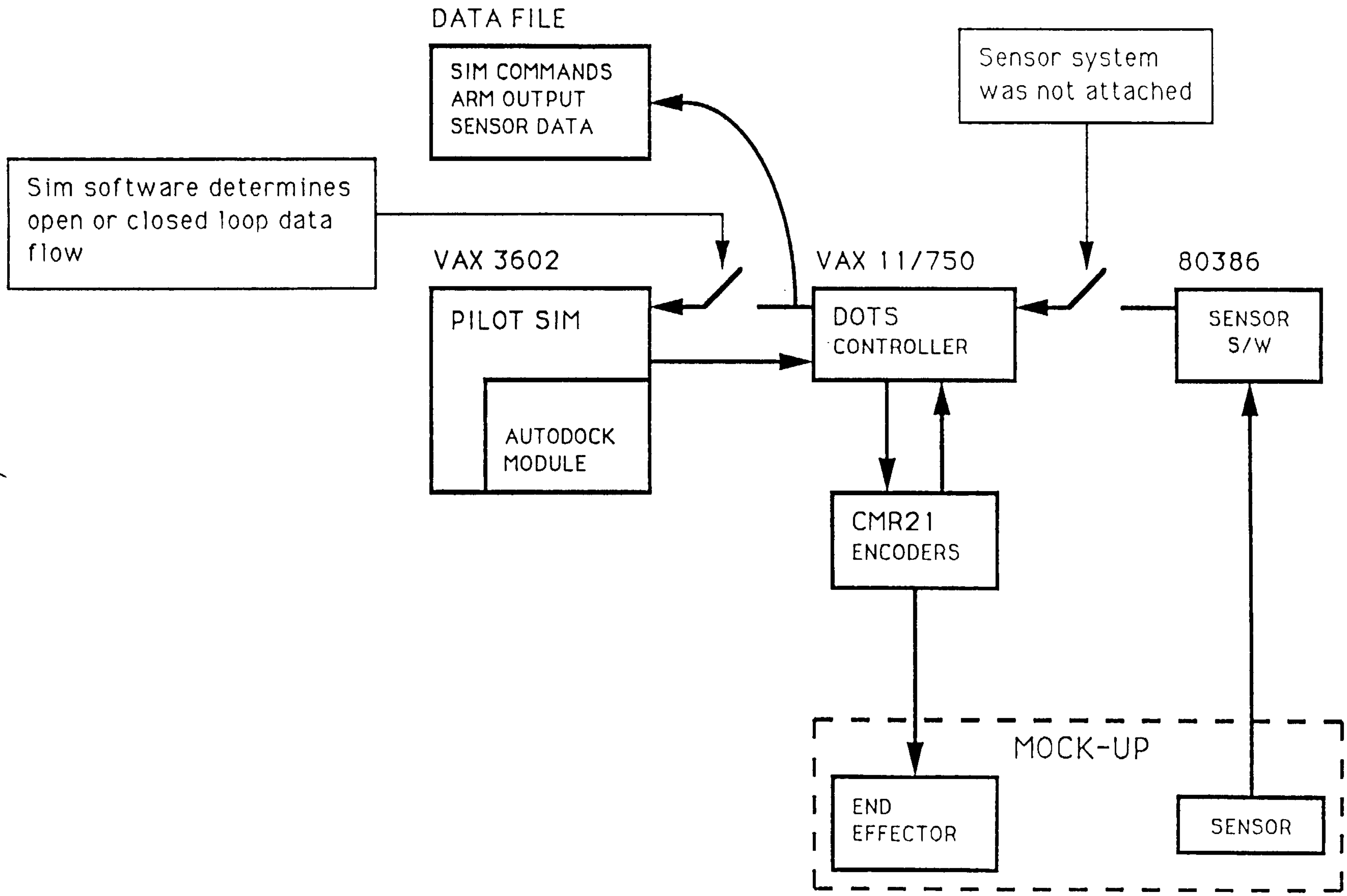
The runs which were performed all had the same initial conditions so that results could be compared. The dynamics simulation software includes an initialization phase where the robotic arm is positioned to conform to the initial conditions and allowed to settle down. During the simulation runs data was collected into history files for post processing and analysis. The data files were created by the robotic manipulator arm controller and the dynamics simulation.

To measure the performance of the sensor it was necessary to calibrate the robotic arm. The reference point which was used to zero the arm was the perfect dock position between the chase vehicle mock-up and the target mock-up. The chase vehicle mock-up at the end of the arm was positioned manually to the zero location then the joint encoder readings from the arm were taken and the absolute position was computed by the software. This was done several times to be sure of the encoder readings and to check the correlation of the resolved positions.

The repeatability of the arm positioning was verified by moving the arm to a random location under manual control and commanding it to return to the zero position under computer control using the newly established origin point. Absolute arm position measurements for arm configurations other than the zero state were also taken. In addition to the calibration tests for the overall arm positioning, procedures were run to verify and correct the absolute encoder output values for each of the individual degrees of freedom for the arm.

A final test which was run was a dynamic motion test in which the linearity of the arm motion was measured when combining two translational axes. This test revealed the basic step resolution of the arm and small, high frequency non-linearities on the order of 0.02 feet in magnitude.

FULL MOTION SIMULATION CONFIGURATION



C-4

5 OBSERVED SENSOR AND CONTROL LOOP PERFORMANCE

The MSFC optical sensor was used for the autodocking runs. This sensor system consists of a video camera, two illuminators operating at different frequencies, reflectors and filters mounted on the target spacecraft, and image processing hardware. The reflectors form spots when illuminated and are visible to the video processing hardware. From the known geometry of the reflectors and the characteristics of the video system, it is possible to extract range, bearing and attitude information by isolating and analyzing the spots.

When the two vehicles are lined up exactly on axis, the image of the sensor target will appear as three equally spaced collinear spots which are horizontal and centered in the image. Range information is extracted from the pixel distance between the two outer dots. Relative bearing information is derived by measuring the pixel offset from the center of the image of the midpoint of the line segment connecting the outer two dots. Roll information is given by the angle of the line between the outer two dots with respect to horizontal. Pitch and yaw angles of the target are computed by measuring the pixel offset of the center spot from the midpoint between the outer two dots.

The optical sensor in its current configuration is very accurate at close range and is more than adequate for the purposes of autodocking. Sensor performance is quite sensitive to range, however, with the noise magnitude increasing proportional to the target range. Bias errors were encountered and were attributable to normal sensor mounting misalignments with respect to the chase vehicle body axis. Because of the way that target position in the Y and Z axes is computed using the relative bearing angles, these axes are especially susceptible to range dependent noise. Attitude information is also much less accurate at longer range due to the smaller image size and loss of detail.

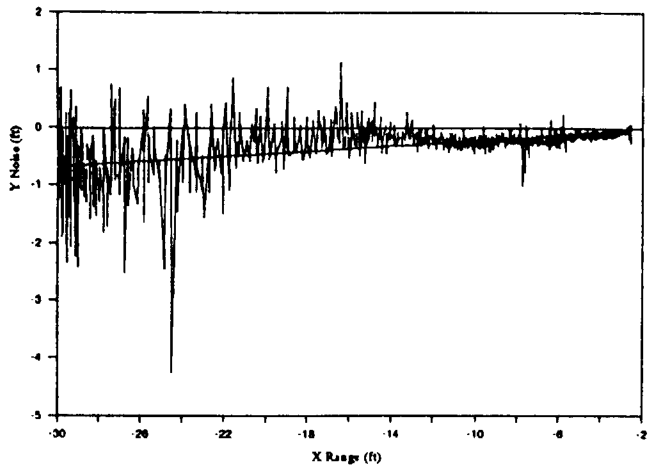
The noise magnitude in the X axis is on the order of ±0.5 feet at a range of 30 feet and decreases to ±0.1 feet at a range of 2 feet. The noise magnitude is roughly proportional to the range. The Y and Z axes are much noisier. The figure shows the sensor noise and bias characteristics for the Y axis. Both Y and Z axes behave in much the same way with noise magnitude increasing linearly with range. At 30 feet the noise magnitude is about ±1.2 feet with occasional spikes of twice that magnitude. At closer range the noise magnitude diminishes to less than ±0.1 feet. Sensor bias is visible on the plot as the solid line through the sensor noise.

The MSFC optical sensor system performs well but the noise levels are unexpectedly high, especially at ranges greater than 15 feet. Another annoyance is the amount of lag in the system. The noise in the system is due to angular errors at longer range when the image of the reflectors is small. This affects the Y and Z outputs from the sensor most adversely. The time lag in the system is due to the three computers which must act in harmony and the delay in moving the robotic arm.

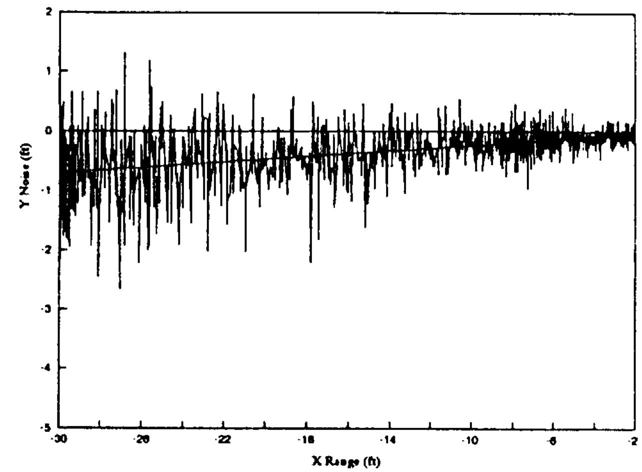
The behavior of the optical sensor has been analyzed and a software model of the sensor has been created, allowing test runs to be performed without requiring access to the actual hardware. The plots show the output from the real sensor and the simulated sensor and reveal that the simulated sensor compares favorably with the actual sensor behavior.

It is apparent that some sort of filtering for the data is necessary. Several filtering techniques were employed but the most promising one is the quadratic curve fitting filter. This filter works by fitting a second order curve through the sensor data, taking into account the motion induced by the thruster activity. This filter also allows the elimination of lag effects since position and velocity can be extrapolated from the curve fit. The performance of this filter is shown in the figure.

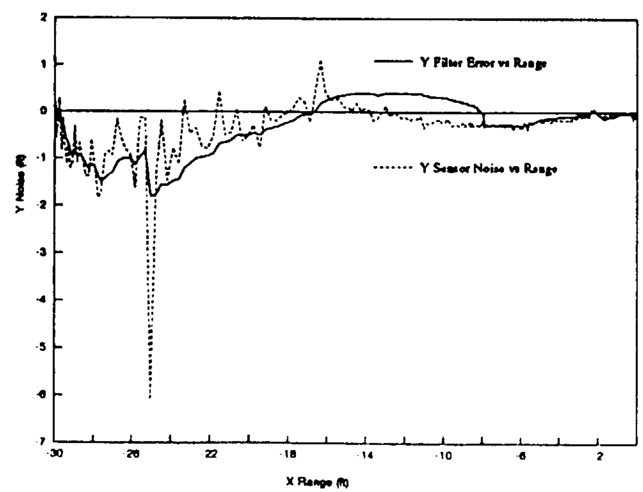
SENSOR AND FILTER PERFORMANCE



OBSERVED SENSOR NOISE



SIMULATED SENSOR NOISE



FILTER PERFORMANCE

The control loop which was tested at the MSFC Flight Robotics Laboratory was the Piecewise Linear C-W Approach. This control loop produces adequate docking performance but there is still much room for improvement. The main problem with the control loop is the selection of the gains, burn duration limits and velocity thresholds. These parameters are not yet optimized and much improvement can be achieved by refining these values for better efficiency and tighter control.

During the initial tests of the control loop it appeared that the system was over controlled. The fuel consumption was excessive and there was too much oscillation in the system, especially in the Y and Z axes. Part of the problem was that the burn duration limits were not set properly. The minimum burn duration was too long, not allowing the required fineness of control, and the maximum burn duration was set too high, allowing large changes in delta-V on each control cycle. This large delta-V conspired together with the sensor and actuator time lag to cause velocity overshoot and subsequent oscillations leading to poor control and high fuel consumption. The fix which was implemented was to reduce the minimum burn duration and restrict the maximum burn per control cycle. The side effect of these changes was a reduction in delta-V capability leading to insufficient braking authority. The control loop performs braking when the stationkeeping goal is less than the look ahead time away in the future. Unfortunately because of the selection of short look ahead times and the maximum burn limit, the system tended to overshoot its mark with inadequate braking capability. This once again led to excessive oscillation.

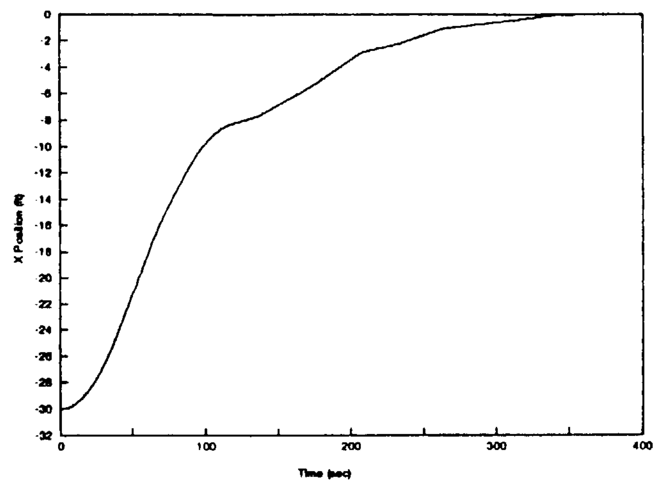
During the runs it was observed that the control loop would rarely burn a single translational axis but would almost always burn X, Y, and Z axes simultaneously. This problem was due to the way that the velocity threshold was computed. The velocity threshold is the mechanism by which a deadband is introduced into the control loop. When the magnitude of the necessary velocity change was less than this threshold value, no burn would take place, effectively creating a velocity deadband. The problem with this scheme was that the velocity used was the magnitude of the velocity vector, not the individual orthogonal components. So if the X velocity change exceeded the threshold, Y and Z would be commanded to burn as well, albeit for a very short time. These three axis burns are not efficient, requiring many thrusters to operate simultaneously. The solution was to separate the velocity components and perform velocity change comparisons with three separate thresholds, one for each axis. This does indeed reduce the number of extraneous Y and Z axis burns.

Although the system deadbands were set too loose and the velocity thresholds were set too high, the control loop was still stable. The plot shows the X position of the chase vehicle with respect to the target vehicle as a function of time. As the X range decreases with time and the velocity ramps down as the approach to dock is made. The approach is asymptotic to the 0 range horizontal axis at the top of the graph.

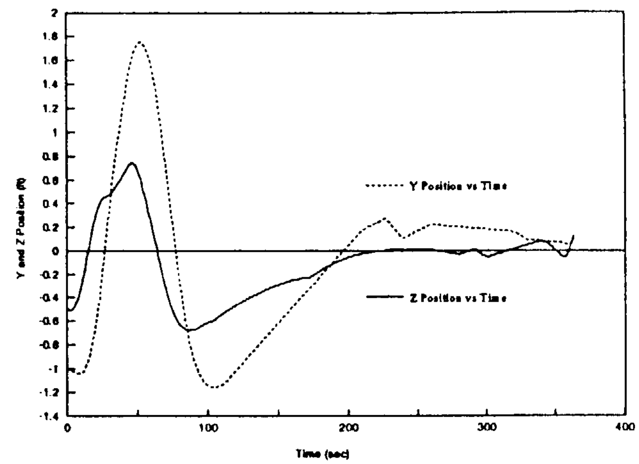
The other figure shows that things were not as well behaved in the Y and Z axes. Instead of smoothly approaching the 0 axis, both Y and Z show oscillatory behavior. This oscillation can be attributed to two causes. The main culprit is the control loop parameter selection. The second cause is the sensor behavior in Y and Z.

Many lessons were learned during our testing at the Flight Robotics Laboratory. These lessons basically fall into three categories: sensor, filter, and control loop. We have gained a much better understanding of how optical sensors behave and how to deal with their characteristics and limitations and know of several modifications which should be made to improve performance. We know about the data filtering requirements and the improvements needed for the current filter. Lastly, we understand the behavior and limitations of the control loop and know what we need to do to fix it.

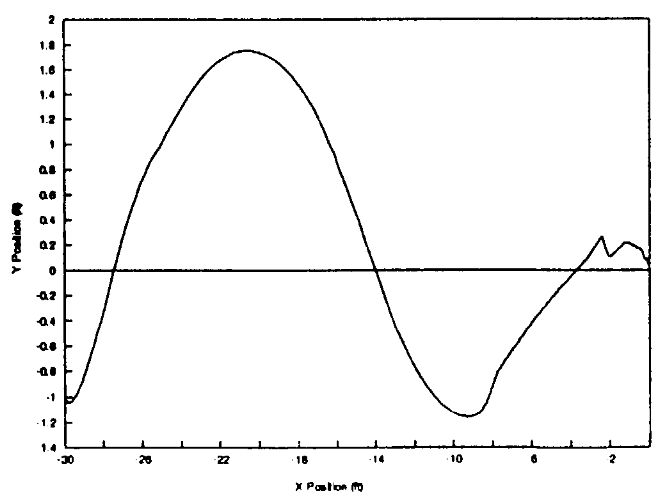
PIECEWISE LINEAR C-W APPROACH CONTROL LOOP PERFORMANCE



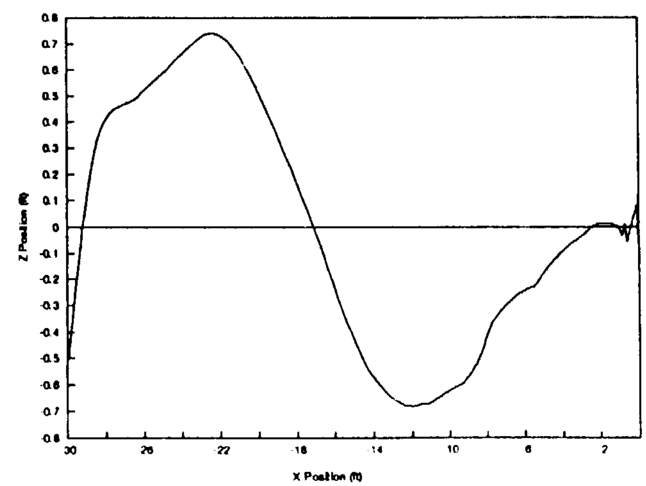
X POSITION VS TIME



Y AND Z POSITION VS TIME



Y POSITION VS X



Z POSITION VS X

6 SIX DEGREE OF FREEDOM CONTROL STRATEGIES

In order to expand the 3 DOF docking algorithms developed so far, it is necessary to lay some ground rules and develop strategies for 6 DOF control. It is necessary to create a control system which is capable of dealing with off nominal contingencies, such as loss of sensor lock, in a safe and reasonable way. In some cases it may be possible to correct the fault by performing some action, such as maneuvering to re-acquire sensor lock, and in other cases it may be necessary to return to some safe condition and abort the mission. As much as possible we would like to avoid this final option by creating an algorithm which is capable of operating in spite of the fault, correcting the fault, or patiently waiting until the fault goes away (waiting for better lighting conditions for example).

An initial set of rules for 6 DOF control is presented in the table in the proposed order of importance (most important rules first). The left side of the table shows the 6 DOF control ground rules and the right side describes the details and rationale behind the rule.

The first concern for autonomous operations is mission safety. The relative geometry between the chase vehicle and the target spacecraft must be monitored at all times so that collisions may be avoided. Safe approach velocity profiles must be adhered to and a safe approach corridor must be defined for each target. Typical safe closing velocities would be 0.1 ft/sec from 100 feet range to 10 feet, 0.05 ft/sec from 10 feet to 1 foot, and 0.01 ft/sec at less than 1 foot range. If these limits are exceeded or a danger of collision exists then action must be taken to reduce velocity or back away from the potential collision circumstances.

During the autonomous docking procedure the amount of uncertainty in the estimated relative state vector between the target and the chase vehicle must be computed and kept up to date with time. If ever the uncertainty is greater than an acceptable threshold, a back away maneuver must be initiated. The uncertainty is computed as a function of the observed sensor fluctuations and the filter output. If the sensor loses lock inside of a safe standoff range then an immediate back away must be performed.

In order to perform autonomous docking, it is necessary for the system to be able to acquire the docking target automatically. Approaches from long range will be made using a range finding system such as radar and will be along the target's velocity vector. Upon reaching docking sensor range, the system may or may not be able to acquire the docking target depending upon the orientation of the target vehicle. If the docking target is not visible to the system then a preprogrammed series of maneuvers will be performed to allow the sensor to scan the target vehicle and locate the docking target.

If sensor lock is lost, one of three possible actions will take place. If the range where lock is lost is less than the safe standoff range, then an immediate back away will be performed. If we are at a safe range, then we have two choices, maneuver to reestablish lock, or hold position and attempt to regain lock. If lock was lost due to losing the target out of the field of view of the sensor, then a maneuver to slew back to center the docking target within the field of view will be performed. If lock was lost for other reasons such as a temporary sensor dropout, then the current position will be held until lock can be reestablished. This may involve cycling through sensor modes or modifying sensor parameters until lock is regained.

Due to the range dependent nature of the sensor noise, it is important that the control loop be very tolerant of noise at long range. At long range it is difficult to discern relative attitude although bearing angles to the target are easily measured. This supports the strategy of controlling attitude to center the target at longer range and not worrying about aligning the two bodies. At close range the relative attitude information will be more accurate and it is appropriate to align the orientation of the bodies at this time.

6 DOF AUTONOMOUS DOCKING RULES

TRW

- INITIAL SET OF RULES FOR 6 DOF CONTROL IN THE PROPOSED ORDER OF IMPORTANCE (MORE IMPORTANT RULES FIRST)

COLLISION AVOIDANCE	THE CONTROL LOOP MUST AVOID COLLISION BETWEEN THE CHASE VEHICLE AND TARGET SPACECRAFT AT ALL COSTS.
SAFE VELOCITY AND RANGE LIMITS	AT ANY GIVEN RANGE SAFE VELOCITY LIMITS MUST BE ADHERED TO.
SENSOR LOCK STANDOFF RANGE	IF SENSOR LOCK IS LOST AT CLOSE RANGE THEN AN IMMEDIATE SAFE BACK AWAY MANEUVER MUST BE PERFORMED TO REACH A SAFE STANDOFF RANGE.
ACQUIRE TARGET	LOCATE AND LOCK ONTO THE SENSOR TARGET ON THE TARGET VEHICLE.
MAINTAIN SENSOR LOCK	MAINTAIN LOCK ON THE SENSOR TARGET AND MANEUVER AS NEEDED TO KEEP A SOLID LOCK.
GET ON AXIS	ALIGN THE CHASE VEHICLE WITH THE TARGET'S AXIS.
APPROACH TARGET AND DOCK	IF ALL OF THE ABOVE CONDITIONS ARE MET THEN IT IS APPROPRIATE TO INITIATE A CLOSING VELOCITY WITH THE TARGET AND PERFORM THE FINAL MANEUVERS TO DOCK.

7 CONCLUSION AND FUTURE PLANS

Substantial progress is being made in developing the capability for autonomous proximity and docking operations. The foundation and necessary framework for further development is established and the data obtained so far is providing a wealth of information. The results from the test floor at the MSFC Flight Robotics Laboratory show that autonomous docking can be achieved using data from a real sensor. Equally significant is the demonstration of a sufficiently flexible system architecture which allowed us to quickly integrate the various system components and produce tangible results. This capability forms the basis of a powerful testbed for control algorithm development and sensor validation.

The results from test runs show areas in the system which need refinement, most notably in the control loop and filtering algorithms. Areas of concern in the sensor behavior have also been exposed. We now possess a clear direction to pursue in the development of the next generation of control and filtering algorithms which will address the problems of 6 DOF control and sensor noise mitigation. Techniques for performing autonomous rendezvous and docking and dealing with contingencies are being developed and will be tested shortly.

The development and testing procedures will include extensive computer simulation without the need for actual hardware since we have developed representative sensor simulation models. When we return to the test floor with new algorithms and techniques we will be able to achieve successful results in a much shorter period of time and we will know in advance the potential problem areas we are likely to encounter.

In addition to demonstrating the validity and performance of the 6 DOF control laws new sensor technologies will be tested and evaluated. These sensors will be integrated into the testbed as soon as they are available towards the end of 1990 and the beginning of 1991. At that time we will be able to demonstrate autonomous docking procedures under a variety of conditions with a collection of different sensors. Contingency resolution will also be demonstrated along with nominal docking operations.

8 ACKNOWLEDGEMENTS

We would like to acknowledge the efforts of the following people without whose help we would not have succeeded.

Ricky Howard, Bill Jacobs, and Mike Book of MSFC for their work in creating the sensor and keeping things together in the Flight Robotics Laboratory.

Charles Naumann and Pat Tobbe of Control Dynamics for their work in creating the Dynamic Overhead Target Simulator (DOTS) and integrating the 6 DOF simulator to the robotic manipulator.

Anthony Miller of TRW for all of the preliminary work in making the testbed a functioning simulation and test tool.

Teri Morrison and Wayne Teng of TRW for their work in analyzing the sensor behavior and creating a simulation to mimic the sensor characteristics.

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Space & Technology Group

CONCLUSION AND PROGRESS

- AUTODOCK HAS BEEN DEMONSTRATED USING STRAIGHTFORWARD TECHNIQUES AND REAL SENSOR HARDWARE
- SIMULATION TESTBED ESTABLISHED AND VALIDATED
  - ROBOTIC MOTION SYSTEM
  - 6 DOF DYNAMICS SIMULATION
  - SENSOR INTERFACE
- TEST ALTERNATIVE SENSORS
- IMPROVE NOISE MITIGATION TECHNIQUES
- 6 DOF ALGORITHM DEVELOPMENT FOR MORE COMPLEX SCENARIOS
  - TARGETS NOT ALIGNED WITH V-BAR
  - FLY AROUNDS
  - SENSOR DROPOUT CONTINGENCIES
  - RADAR APPROACH AND SENSOR ACQUISITION AND HANDOFF
- TEST VARIOUS DIFFERENT SPACECRAFT CONFIGURATIONS
  - LARGE CG OFFSETS
  - PROPULSION CONFIGURATIONS
  - STABILITY AND MANEUVERABILITY CONCERNS
- HYBRID CONTROL LOOPS WITH HUMAN INTERACTION OR INTERVENTION
  - HUMAN INITIATED DOCKING ABORT OR COMPLETION
  - OPERATOR AID TO CONTROL LOOP SUCH AS TARGET DESIGNATION

☆ U.S. GOVERNMENT PRINTING OFFICE: 1990—761-014/20377